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MLS Mathematical Model Validation Study Using Airborne MLS Data From Atlantic City International Airport Boeing 727 Elevation Shadowing Flight Tests

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16. Abstract

This study evaluated the performance of the Microwave Landing System (MLS) math model by comparing the results of the model's simulation errors along a flightpath with actual flight check measurements. The data collected for this study were designed specifically to evaluate the shadowing aircraft computations of the model. The results showed that there was some agreement between measured and modeled data, but it was concluded that further development of the shadowing aircraft computations is required.

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EXECUTIVE SUMMARY

This Microwave Landing System (MLS) mathematical model validation study evaluated the performance of the MLS math model by comparing the results of the model's simulation of flight profiles flown at the Federal Aviation Administration (FAA) Technical Center (Atlantic City International Airport, NJ) with actual airborne data collected during the test flights. This study and the flight profiles flown were designed specifically to address the effects of shadowing of MLS signals by aircraft directly in front of the MLS elevation system.

The study found that comparisons of model output with real world data showed some agreement. Discrepancies between the two were explainable as either the model's sensitivity to input parameters or the model's strategy for simulating a shadowing aircraft silhouette. The study supports the conclusion that the MLS math model requires further development with respect to modeling of shadowing aircraft.

PURPOSE

The purpose of a validation study is to evaluate the performance of the Microwave Landing System (MLS) Mathematical Model by comparing the results of the math model's simulation of flight test profiles with actual airborne data collected during these test flights. This specific study addresses the shadowing of MLS elevation signals by aircraft located directly and closely (approximately 190 feet) in front of the elevation system. The airborne data were collected during a special series of flight tests designed and conducted at the Federal Aviation Administration (FAA) Technical Center to study shadowing aircraft effects.

BACKGROUND

THE MLS MATHEMATICAL MODEL.

The MLS Mathematical Model simulates the operation of an MLS for the purpose of predicting the effects of the airport environment on the accuracy and quality of the guidance signal information arriving at the aircraft. The scenario or airport environment to be modeled is defined by three sets of input data. One set of data describes the obstacles in the airport environment (buildings, aircraft, terrain features) that might have reflective (multipath) or diffractive (shadowing) effects on the transmitted signal. The position and signal characteristics of the MLS antenna systems are defined by a second set of data, and a third set provides the coordinates of the flightpath. The model uses these data to predict (1) the effects of the airport environment on the propagated signal, and (2) the receiver output angle errors caused by these effects.

Originally developed by the Lincoln Laboratory of the Massachusetts Institute of Technology (MIT), the MLS Mathematical Model has been extensively revised and baselined by personnel at the FAA Technical Center. Additional validation of the model is required to determine whether the model continues to perform satisfactorily in representing the real world and to investigate the model sensitivities to input parameters. The approach to validation taken in this study and the philosophy of interpreting the results are discussed in detail in the Concepts Analysis Division Report ACD-330-90-04, "Approach to Validation of the MLS Mathematical Model" (Linda Pasquale and Jesse D. Jones).

MLS ELEVATION SHADOWING AIRCRAFT TESTS.

At the request of the Great Lakes Region, the FAA Technical Center conducted an operational demonstration of an MLS installed temporarily to serve runway 22L at Chicago's Midway Airport. During one of the approaches, the pilot of the Technical Center's demonstration aircraft reported a fly-down Course Deviation Indicator (CDI) deflection during most of the approach, which took him well below the desired 3° glidepath and eventually caused him to abandon the CDI guidance. These effects were later attributed to a DC-9 aircraft holding on taxiway P between the elevation system and the approaching aircraft as indicated by figure 1. Since this occurred during one of the demonstration flights, no tracking or recorded data were available. It should be noted that

the elevation system was temporarily sited for the MLS demonstration and, therefore, no attempt was made to restrict the critical area from moving traffic. Since the taxiway was located well inside the defined elevation critical area, a normal MLS installation would have closed the taxiway or eliminated aircraft from the critical area during an MLS approach, and the observed effects would not exist. Simulations performed later at the Technical Center confirmed that the observed effects could be attributed to the DC-9.

In order to achieve a better understanding of this phenomenon and provide quantitative data for model validation, a close approximation to this scenario was created at the Technical Center. This was accomplished by installing the MLS elevation system near the north end of abandoned runway 17/35 and positioning the Technical Center Boeing 727-100 (N-40) aircraft (similar in size and shape to the DC-9) at two locations in front of it. Flight test data were collected with the B-727 parked at the two locations discussed in this report. Partial orbit, radial, and approach flight profiles were flown for each B-727 position (plus a set of control runs with no shadowing aircraft) with laser tracking to provide accurate positional data. MLS data recorded during these flight tests provide the desired "real world" data which were compared with math model predictions, thereby, offering an opportunity to evaluate the performance of the model in simulating the aircraft shadowing effects.

DATA COLLECTION AND MODELING METHODOLOGY

MLS EQUIPMENT AND SITING.

The MLS test bed system used for these tests was a modified Bendix FAR-171 MLS (models B-21.5-40S and BI-60S) which met the FAA MLS accuracy tolerances in FAA-STD-022b and FAA-STD-022c. The azimuth antenna serving runway 13 had a 2° beamwidth with ±40° proportional azimuth guidance. The elevation (EL) antenna had a 1.5° beamwidth with proportional coverage from +0.9° to +15°. The EL antenna was moved for these tests to a location 490.92 feet north offset from the centerline of runway 13/31 and 171.42 feet east offset from the centerline of runway 17/35 (taxiway for these tests). The field distance measuring equipment (DME) at Atlantic City was used for ranging since no precision distance measuring equipment (DME/P) was available for these flight tests. The FAA Technical Center laser tracking facility provided ground-based tracking positional data for the aircraft. The shadowing aircraft locations were marked along a line parallel with the centerline of runway 17-35 and 130.6 feet from the EL phase center in order to approximate the Midway scenario. A map of the siting and obstacle geometry is shown in figure 2. The two aircraft locations (defined at the center of the fuselage) used for this study are identified in figure 2 as SAP4 and SAP5. The aircraft shown is positioned at SAP5.

ENGINEERING FLIGHT TESTS.

The FAA aircraft used for the flight tests, a Convair-580 (N-91), included a data collection system designed, built, installed, and tested at the Technical Center. This system records data from the MLS angle receivers, the DME

interrogator, and the Radio Telemetering Theodolite (RTT), when used. Flight profiles included level ±40° partial orbits (to observe the shadowing effects over a range of azimuth angles) through the MLS coverage volume for 3.0° and 3.4° elevation angles at a distance of 7 nautical miles (nmi) from the DME. Tracked approaches from a range of approximately 10 nmi from threshold at angles of 3.0° and 3.4° demonstrate the shadowing aircraft effects for standard approach flightpaths. In addition, level centerline approaches at 2000 feet were flown to investigate the shadowing effects of the aircraft over a large range of vertical angles. All the runs flown were reviewed, and a typical orbit, approach, and radial selected for analysis from both shadowing aircraft positions. A complete series of tracked runs without any shadowing aircraft was also flown in order to determine the typical effects of the airport for baseline data.

FLIGHTPATH CREATION.

Flightpath data can be entered into the MLS Math Model in either of two ways. The coordinates of the flightpath segment endpoints can be included in the formatted input file, a method appropriate for theoretical flightpaths that are calculated mathematically. In the alternate method used for this study, the model reads flightpath coordinates directly from a second input file. This method allows the flightpath to be defined in greater detail and is the appropriate method to use when actual flight data are available. Flightpaths are created from the laser data collected during the flight tests by translating and rotating the X, Y, and Z coordinates provided (relative to the laser) to the model coordinate system. The software developed to reduce and analyze airborne data and create a measured flightpath is documented in the Concepts Analysis Division Report DOT/FAA/CT-ACD33090/08, "Software for the Creation and Analysis of Measured Flightpaths from Laser Tracker Data" (Linda Pasquale).

MODEL INPUT DATA.

No significant sources of multipath exist for the MLS elevation siting used during this study. However, parts of the new glide slope shelter, the old glide slope building 166, a fence around a transformer pad near the glide slope, and the concrete surfaces of runway 17/35 and taxiway C in front of the elevation system, were included in the model input file. It was determined in comparative runs that the above obstacles did have a very small effect on the output data. Therefore, they were included in order that the input file would represent the scenario as closely as possible. A shadowing aircraft was included in the input file at either of the two locations used in this study, as appropriate.

The antenna systems specified in the model were the MLS Bendix testbed antenna patterns which had been added to the model for validation purposes. These patterns are a direct match for the MLS antenna systems used for the data collection flights. The measured flightpath option of the model was used to model the appropriate flightpath for the particular flight test being studied. Appendix A is a copy of the input file showing all of the sections used and the specified input parameters. Section 8 shows the coordinates of shadowing aircraft location SAP4. The other shadowing aircraft location (SAP5) is shown in section 8 of appendix B.

DATA PRESENTATION AND ANALYSIS

ANALYSIS OF PLOTS.

The MLS Math Model utilizes two phases of simulation. First, the program BMLST (and the associated plotting program BPLOTT) simulates the signal in space for the specified airport environment and produces plots which identify the multipath and shadowing effects from specific obstacles (buildings, aircraft, ground reflection surfaces). In the second phase, the system model programs BMLSR and BPLOTR simulate the operation of the receiver given the transmitted signal as output from BMLST. Plots from BPLOTR show the receiver error ("raw" error) which is defined as the difference between the actual position of the aircraft (as defined by the input flightpath) and the position as determined by simulation of the MLS. These raw error data are further processed with path following error (PFE) and control motion noise (CMN) filter algorithms. The PFE algorithm, a low-pass filter which removes components of the error data that will not have a measurable effect on the ability of the aircraft to follow the specified flightpath, creates plots that are particularly useful for comparison with actual airborne data because they emphasize the large-scale shape of the data curve. Therefore, the model output for purposes of this validation study is judged primarily on the basis of the PFE error plots with support from shadowing plots which identify specific regions of signal disruption.

Real world data, recorded by the airborne data collection system, are processed by data reduction and graphics software that produce plots designed to facilitate comparison with the model PFE error plots previously described. All flightpaths are described by "differential error" plots which show the angle error against the appropriate X-axis for the particular flightpath. The angle error is calculated by subtracting the angle determined by the laser tracker coordinates from the MLS receiver angle and filtering the resulting value with a PFE algorithm. Similarly, the model receiver error is calculated by subtracting the angle determined by the flightpath coordinates from the angle determined by the MLS system simulation. The resulting error is PFE filtered. Thus, the model error values and the airborne error values are both PFE filtered and plotted against appropriate X-axis values referenced to the MLS azimuth antenna for easy comparison and analysis of the location and magnitude of differences.

Approach and radial flightpaths are described by plots which show the angle error against the distance from the azimuth antenna. Orbit flightpaths are plotted similarly to the approach flightpaths; however, these values are plotted against the azimuth angle of the MLS azimuth system.

This study will show that the errors generated by the model are comparable in magnitude to the measured errors. However, the errors, particularly in the case of orbits, are not in the same location as the measured errors. These differences result primarily from the methodology of modeling a shadowing aircraft as two rectangular plates. Figure 3 shows the two rectangular plates used by the model to represent a B-727 aircraft in comparison to the outline of the aircraft. This study will conclude that this method of representing (or defining) shadowing aircraft needs to be improved.

ORBIT FLIGHTPATHS.

Partial orbit flightpaths were flown to examine the effects of diffraction from the tail and fuselage of the B-727 in the horizontal plane. Initially, an orbit without any shadowing aircraft was flown to determine the effects of the Atlantic City Airport without shadowing aircraft. A typical airborne error plot of an orbit with no shadowing aircraft is shown by figure 4. The corresponding model PFE error plot for this flightpath is presented in figure 5. Neither plot shows any significant interference to the MLS guidance signals from the airport. A comparison of the two plots, however, illustrates the noisiness of flight data in comparison to modeled data and supports the philosophy of comparing modeled with measured data for large scale features only.

The first shadowing aircraft position investigated (SAP4) situated the B-727 with the nose of the aircraft touching the extended boresight of the elevation system. The airborne data collected for this scenario are presented in figure 6. This plot shows that significant (and off scale) errors are generated by the shadowing aircraft between the azimuth angles of 5° and 25°. The modeled data for this flightpath, shown in figure 7, also show significant errors, but between the azimuth angles of 0° and 16°, and the errors remain on scale. Therefore, the model shows the same effect but with the error displaced. The statement that the plots show the same effect is to be construed to mean that they have the same type of error signature. The model plot, however, does not show the positive off-scale error observed on the measured error plot.

Two possible reasons are offered to explain the differences. First, although the survey marks used to position the aircraft were precisely known, the actual aircraft position and orientation were not measured after positioning nor was the ground elevation of the runway surface at the shadowing aircraft positions determined by the survey. At the close distances involved in this study, a small difference in the actual aircraft position can cause a large difference in the observed location of an effect. Second, the model represents the aircraft silhouette for shadowing purposes as two rectangular surfaces (see figure 3). This representation of the aircraft shape does not accurately match the curvature of the aircraft nose and the slope of the leading and trailing edges of the aircraft tail. This simplification of the aircraft silhouette in the model can also lead to the displacement of effects from their true location.

The other shadowing aircraft location (SAP5) tested centered the fuselage on the MLS elevation system boresight. Figure 8 is the airborne error plot for this scenario, and figure 9 is the corresponding model plot. Again, these figures show similar amplitude effects between measured and modeled data but with the effects in different locations with respect to azimuth angle.

RADIAL FLIGHTPATHS.

Level centerline approach flightpaths were flown to examine the effects of diffraction from the B-727 in the vertical plane. Initially, a level approach without any shadowing aircraft was flown to determine the typical effects of the Atlantic City Airport. A typical airborne error plot for a level

approach with no shadowing aircraft is shown in figure 10. The corresponding model PFE error plot for this flightpath is indicated in figure 11. Neither plot shows any significant interference with the MLS guidance signals from the airport.

At this point in the analysis, it is appropriate to digress briefly from the main objective to discuss an experiment conducted in conjuction with this study to validate the implementation of the ELB15 (elevation test bed) antenna pattern in the model. During the analysis and comparison of the two plots above (figures 10 and 11), an attempt was made to see how closely the small scale effects between measured and modeled data could be matched. This analysis concentrated on the nonlinearity of the error trace in the modeled data since the primary error mechanism for this scenario is ground reflections. Although the ground for this run includes the separate concrete surfaces of runway 17/35 and taxiway C, a model run with flat homogeneous ground yielded almost identical results. This suggests that the elevation antenna vertical radiation pattern (ELB15) alone is causing the observed effects rather than any obstacles in the environment.

The same scenario was rerun with a different antenna pattern (ELBN, the Basic Narrow pattern from Lincoln Laboratory) to investigate this assumption. Figure 12, the ELBN antenna model plot, shows that, as expected, there is a significant difference between the two model runs (figures 11 and 12). The model error plot (figure 12) for the ELBN antenna pattern, shown in figure 13, has significant errors beyond 6 nmi that are not apparent on the measured data. Figure 14 is a plot of the ELB15 antenna pattern used to generate the error data of figure 11. The effect of the antenna patterns is obvious when one compares these plots (figures 11 and 14) with the corresponding ELBN plots of figures 12 and 13. This experiment shows that the elevation antenna pattern (sidelobe reflections from the ground) is the primary error mechanism in the model for a relatively clean airport environment such as the Technical Center. The ELB15 antenna pattern was obtained from Bendix and installed in the model by Technical Center personnel. The similarity between the measured and modeled data (figures 10 and 11) confirms the implementation of this antenna pattern in the model.

Returning to the primary objective of this study, figure 15 presents the airborne data for a level approach with a shadowing aircraft positioned (SAP4) so that the nose of the aircraft touches the elevation boresight extended. No significant errors are evident on this plot or in the model error plot of figure 16. It is reasonable for this geometry to have no effect on the guidance signal since, as the direct signal does not traverse the shadowing aircraft, only diffraction from the nose or sloped edge of the tailfin would cause errors, and any diffraction from the sloped tailfin would be deflected well above the flightpath.

An aircraft located directly in front of the elevation boresight (SAP5) does, as expected, cause significant errors on a level flightpath, as shown by the measured data of figure 17. The modeled data for this flightpath, presented in figure 18, also show significant errors. A comparison of the two plots shows a displacement between the observed and modeled errors similar to that observed on the plots of orbit data. In addition, the peak errors between 6 and 7 nmi are of opposite signs in the two plots. This is a common occurrence when comparing measured and modeled data and is attributed to phasing

differences between the real world and the precision of the computer calculations. As with the orbit flightpath data, the displacement of errors can be explained as a function of the imprecision of the actual shadowing aircraft location and the simplicity with which the model represents an aircraft silhouette.

APPROACH FLIGHTPATHS.

Standard 3.0° and 3.4° approaches were flown to observe the shadowing aircraft effects on a typical approach path. Since there were no significant differences between the results from the two approach angles, only the 3.0° approaches were selected for presentation. An approach without any shadowing aircraft was flown to determine the Technical Center airport effects on the MLS guidance signal. Neither the measured data, figure 19, nor the modeled data, figure 20, for this approach show any significant errors.

The measured results of an approach with the shadowing aircraft positioned so that the elevation boresight extended touches the nose of the aircraft are shown by figure 21. Neither this plot nor the modeled data of figure 22 show any significant shadowing effects. Although there appears to be a somewhat prominent error peak at approximately 4 nmi, the peak-to-peak error is typical of this scenario with no aircraft (see figure 19).

Placing the shadowing aircraft directly in front of the elevation antenna boresight does cause significant errors on an approach as seen in the measured data plot of figure 23. The model error plot of figure 24 also shows significant errors. These errors are of similar magnitude but opposite sign between about 3 to 7 nmi. Between 1.5 and 3 nmi, however, the model does not correctly depict the measured data. In this region the errors would be generated by diffraction from the shadowing plate representing the fuselage, whereas, any diffraction from the actual aircraft would be moving down the sloped surface of the B-727 from the tail towards the nose. In order to approximate the effects of the sloped surface, an additional modeling simulation was performed with the B-727 vertical position 1 foot lower than it was for figure 24. The results of this simulation, figure 25, were much closer to the measured data between 1.5 and 2.5 nmi, and the errors decreased in the 3 to 7 nmi range as compared to those shown in figure 24. These plots show that, for this scenario, the model does not correctly represent the shadowing aircraft effects with respect to location and is sensitive to the vertical location of the aircraft. The model is inaccurate because of the inability of the fuselage plate to represent the sloped surface of the fuselage silhouette and because the top of the plate is located below the actual top of the fuselage. Another source of differences (although considered small) is the vertical position of the aircraft input to the model. This value (within 0.2 foot) was estimated from survey data since the actual aircraft position was not surveyed after positioning.

THEORETICAL FLIGHTPATHS.

Analysis of airborne data and model simulations using measured flightpaths indicates that the model's method of representing shadowing aircraft needs improvement. However, for completeness, the possibility that the discrepancies between airborne and modeled data are a side effect of the measured flightpath itself must be investigated. In order to test this

hypothesis, every scenario was also modeled with a calculated segmented flightpath approximating the original measured flightpath. Orbits were simulated by a constant radius and altitude using 35 segments. Radials were represented by one segment at a constant altitude. Approaches were simulated by two segments defining both the level portion of the initial approach and a constant descent along the glidepath. In most cases, the results from the measured and calculated flightpaths were equivalent. In particular, any out-of-tolerance conditions observed using the measured flightpath were also apparent with the calculated flightpath.

The results of this experiment can be illustrated by one of the orbit flightpaths for shadowing aircraft position 4. The measured flightpath for run 3 on December 16th, logged as a 2000-foot orbit, never exceeded an altitude of 1927 feet above ground level (AGL) and averaged 1858 feet. The results of a model run with this measured flightpath were presented in figure 7. This scenario was repeated with the calculated orbits at 2000 and 1858 feet AGL. The model error plots from these simulations, figures 26 and 27, respectively, compare very well to the measured flightpath data of figure 7. This shows that the flightpath used for modeling this orbit can vary in altitude (over a range of 150 feet) without introducing any appreciable errors.

CONCLUSIONS

Comparisons of model output with real world data collected during the shadowing aircraft flight tests at the Federal Aviation Administration (FAA) Technical Center show mixed agreement. Discrepancies between measured data and model results are explained primarily by the method (two rectangular plates) used by the model to simulate shadowing aircraft and, secondarily, by the model's sensitivity to input parameters. More detailed surface definitions for shadowing aircraft and more precise location measurements will improve model performance in this area.

It is concluded, therefore, that the Microwave Landing System (MLS) mathematical model inadequately simulates the behavior of an MLS with respect to the effects of shadowing aircraft on the signals arriving at the receiver. Theoretical or calculated straight line (segmented) approximations to the measured flightpaths yield equivalent results and are valid for making model predictions. The results of this validation study support the conclusion that the MLS mathematical model requires improvement to the method used to represent a shadowing aircraft silhouette. The results also show the importance of accurate location measurements for the definition of a shadowing aircraft position.

In addition, this study also provided data to confirm the implementation of the ELB15 Bendix Elevation Test Bed antenna pattern in the model.

RECOMMENDATIONS

It is recommended that further study be performed of the methods used by the model to represent shadowing aircraft and that improvements be developed to minimize the displacement of errors observed in the modeled data. It is further recommended that the location of the aircraft be surveyed after positioning for any future validation studies related to aircraft.

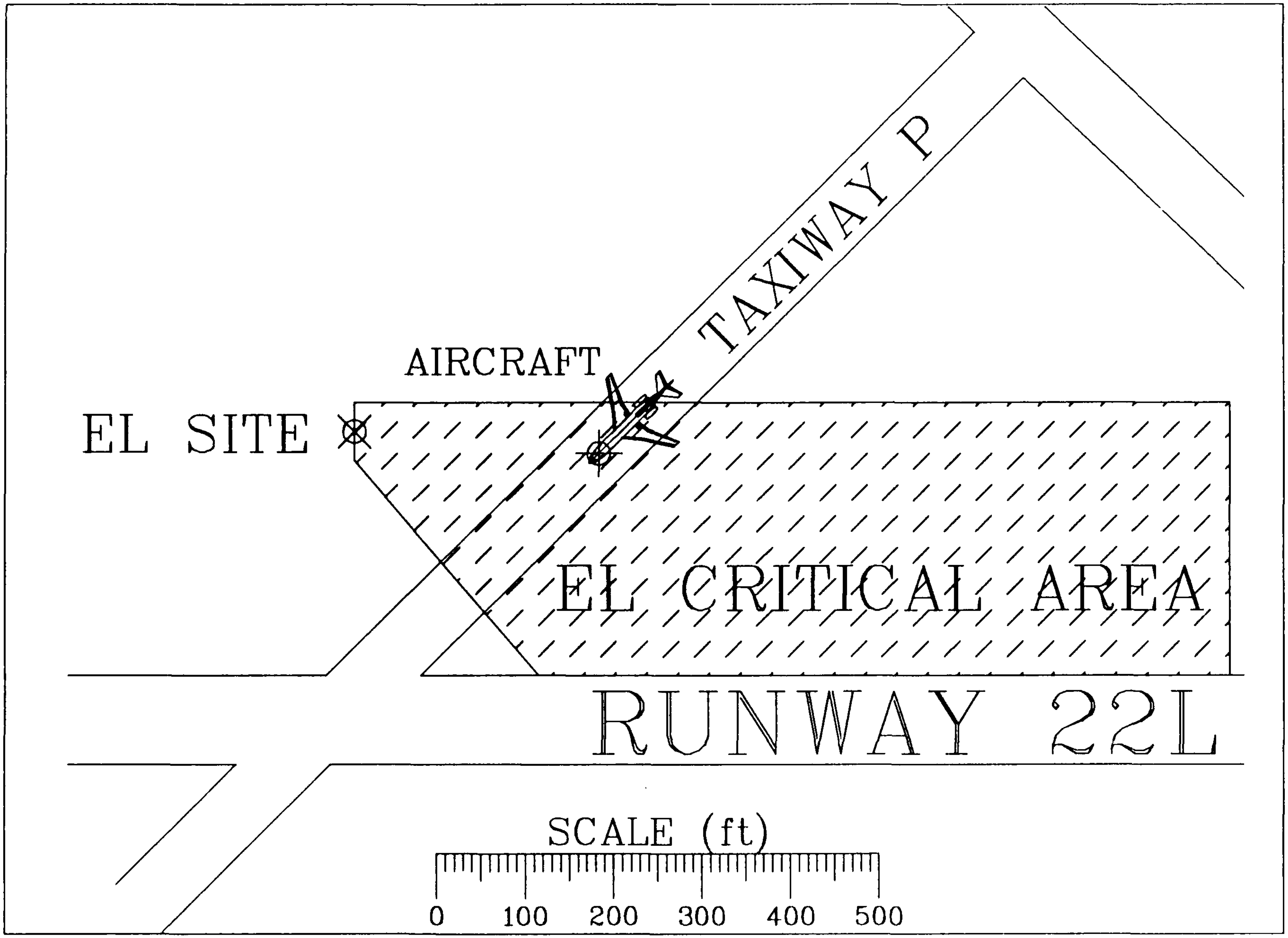

FIGURE 1. MIDWAY MLS ELEVATION SYSTEM SITING AND CRITICAL AREA

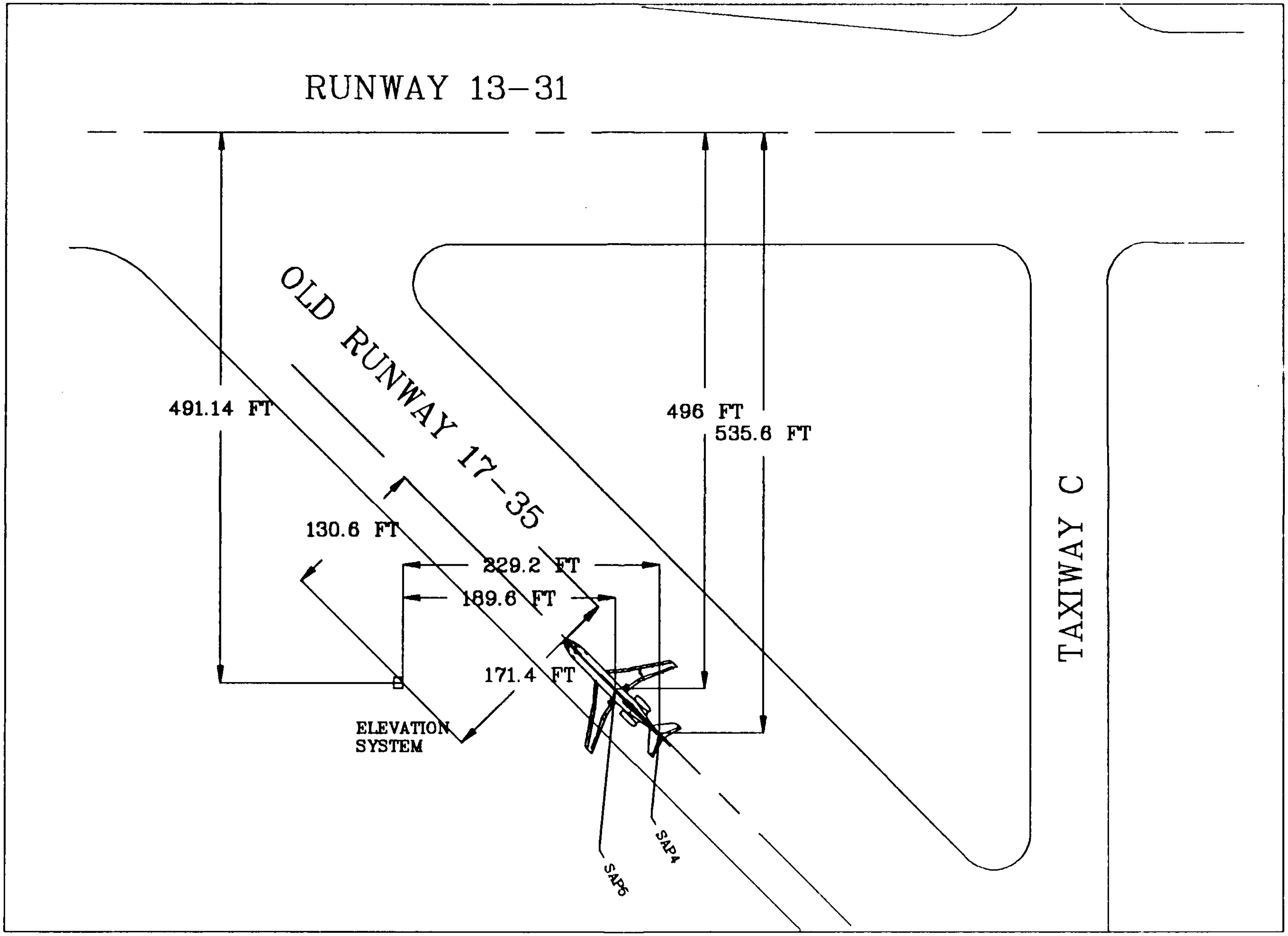

FIGURE 2. SHADOWING AIRCRAFT TEST SCENARIO MAP

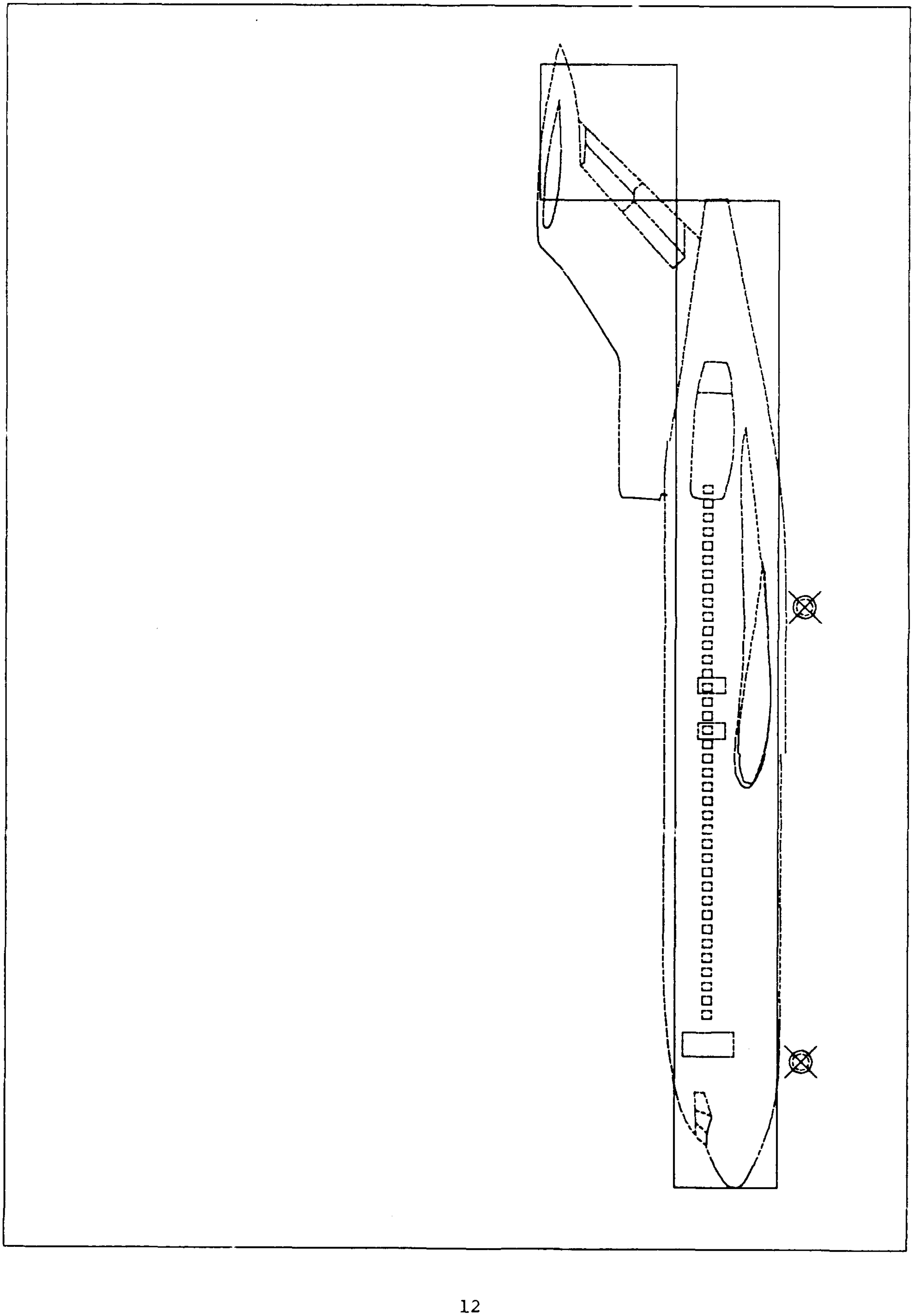

FIGURE 3. MLS MATH MODEL SHADOWING AIRCRAFT PLATES FOR BOEING-727

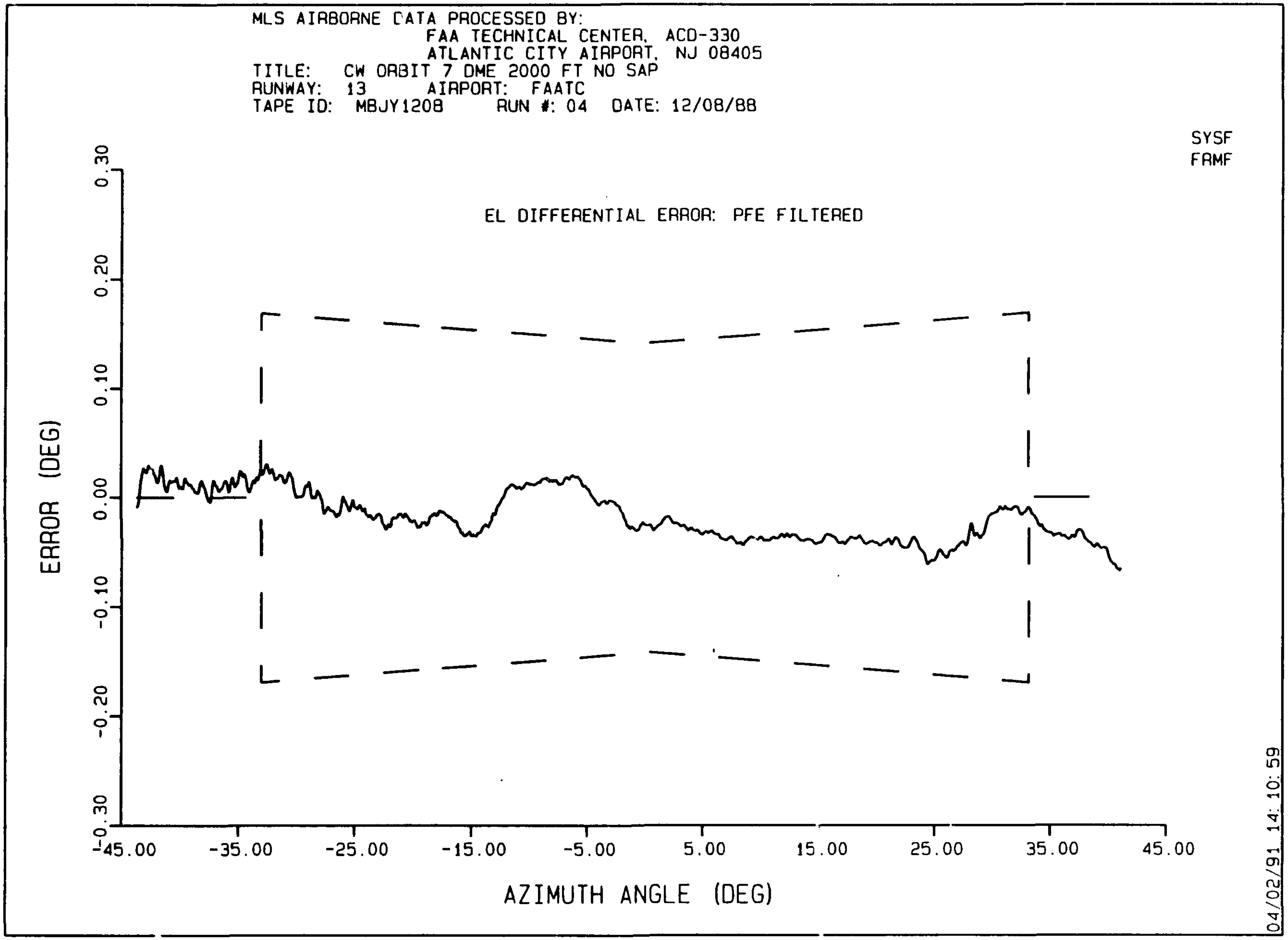

FIGURE 4. ORBIT AT 3.0 DEGREE ELEVATION ANGLE, 7 NMI FROM DME, ELEVATION SYSTEM, NO SHADOWING AIRCRAFT, MEASURED ERROR PLOT

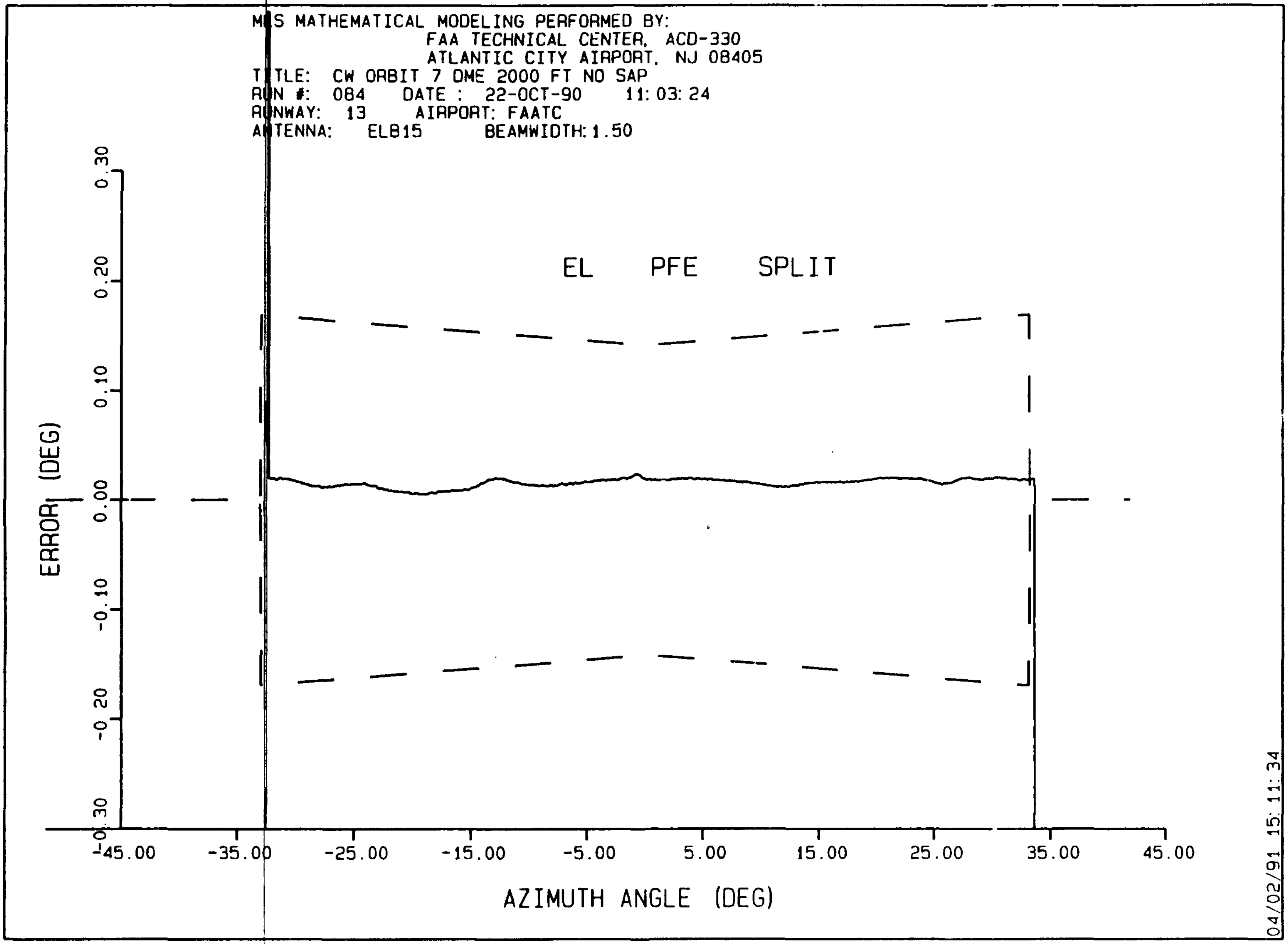

FIGURE 5. ORBIT AT 3.0 DEGREE ELEVATION ANGLE, 7 NMI FROM DME, ELEVATION SYSTEM, NO SHADOWING AIRCRAFT, MODEL PFE FILTERED PLOT

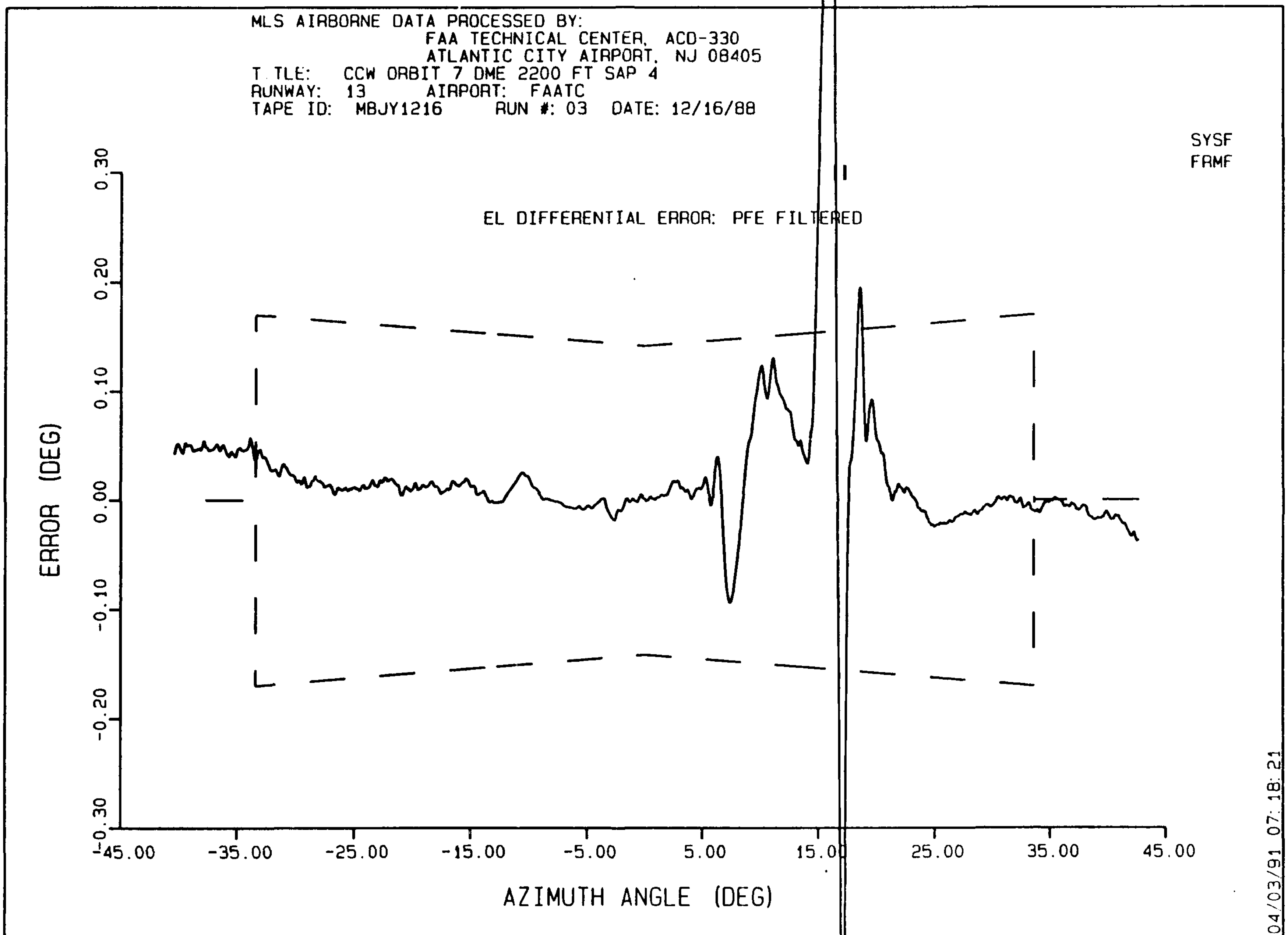

FIGURE 6. ORBIT AT 3.0 DEGREE ELEVATION ANGLE, 7 NMI FROM DME, ELEVATION SYSTEM, SHADOWING AIRCRAFT POSITION 4, MEASURED ERROR PLOT

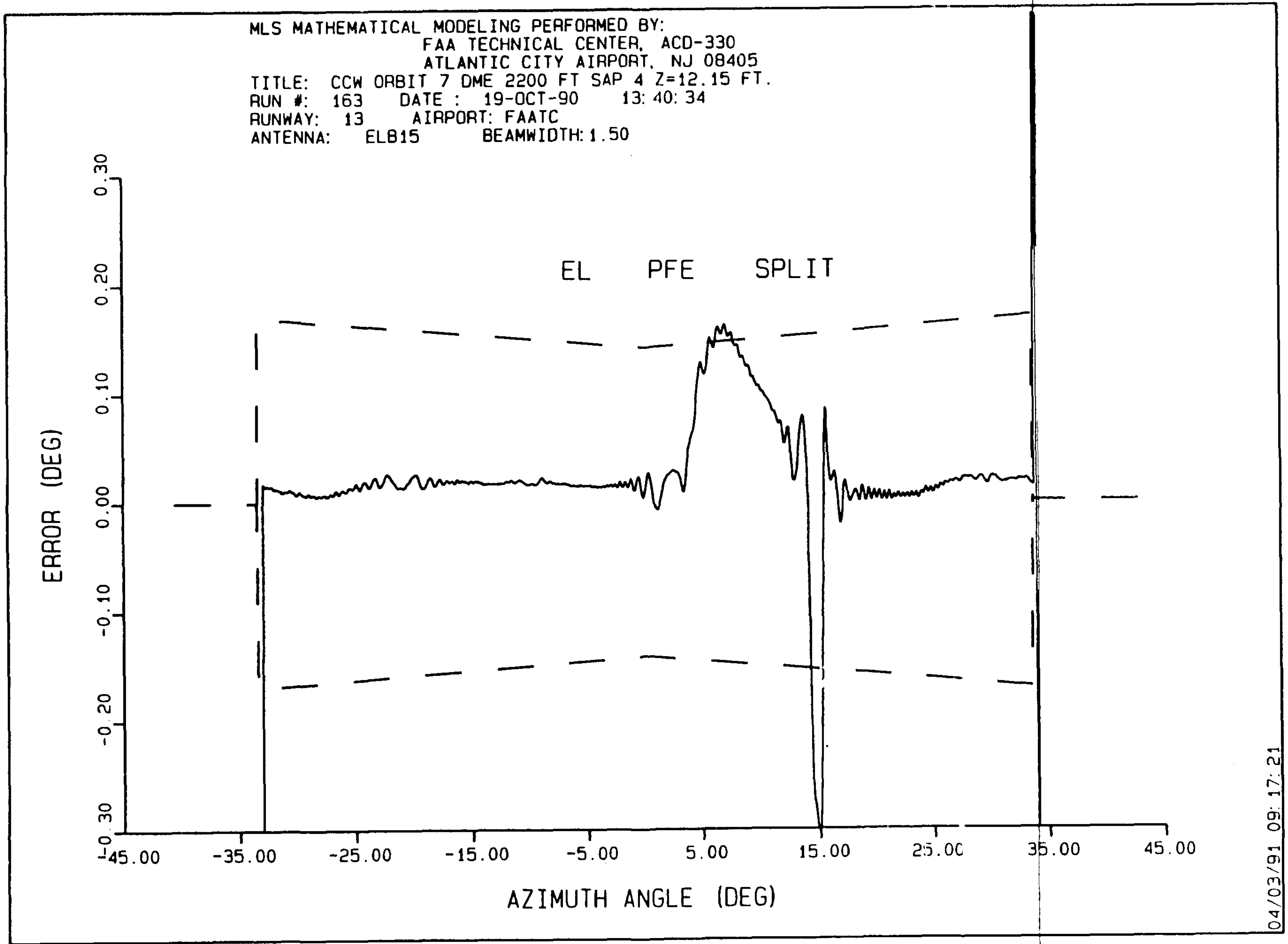

FIGURE 7. **ORBIT AT 3.0 DEGREE ELEVATION ANGLE, 7 NMI FROM DME, ELEVATION SYSTEM, SHADOWING AIRCRAFT POSITION 4, MODEL PFE FILTERED PLOT**

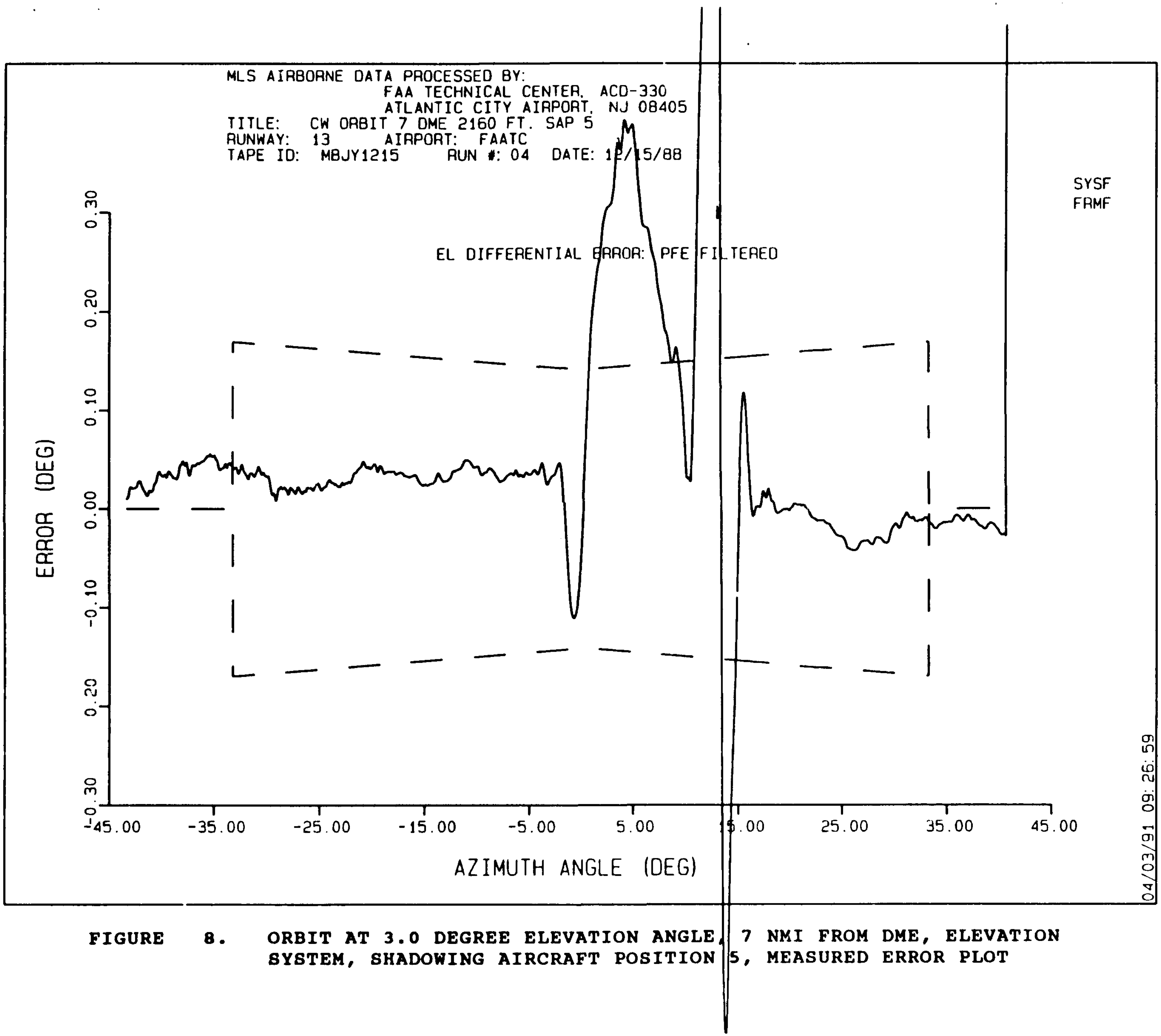

FIGURE 8. ORBIT AT 3.0 DEGREE ELEVATION ANGLE, 7 NMI FROM DME, ELEVATION SYSTEM, SHADOWING AIRCRAFT POSITION 5, MEASURED ERROR PLOT

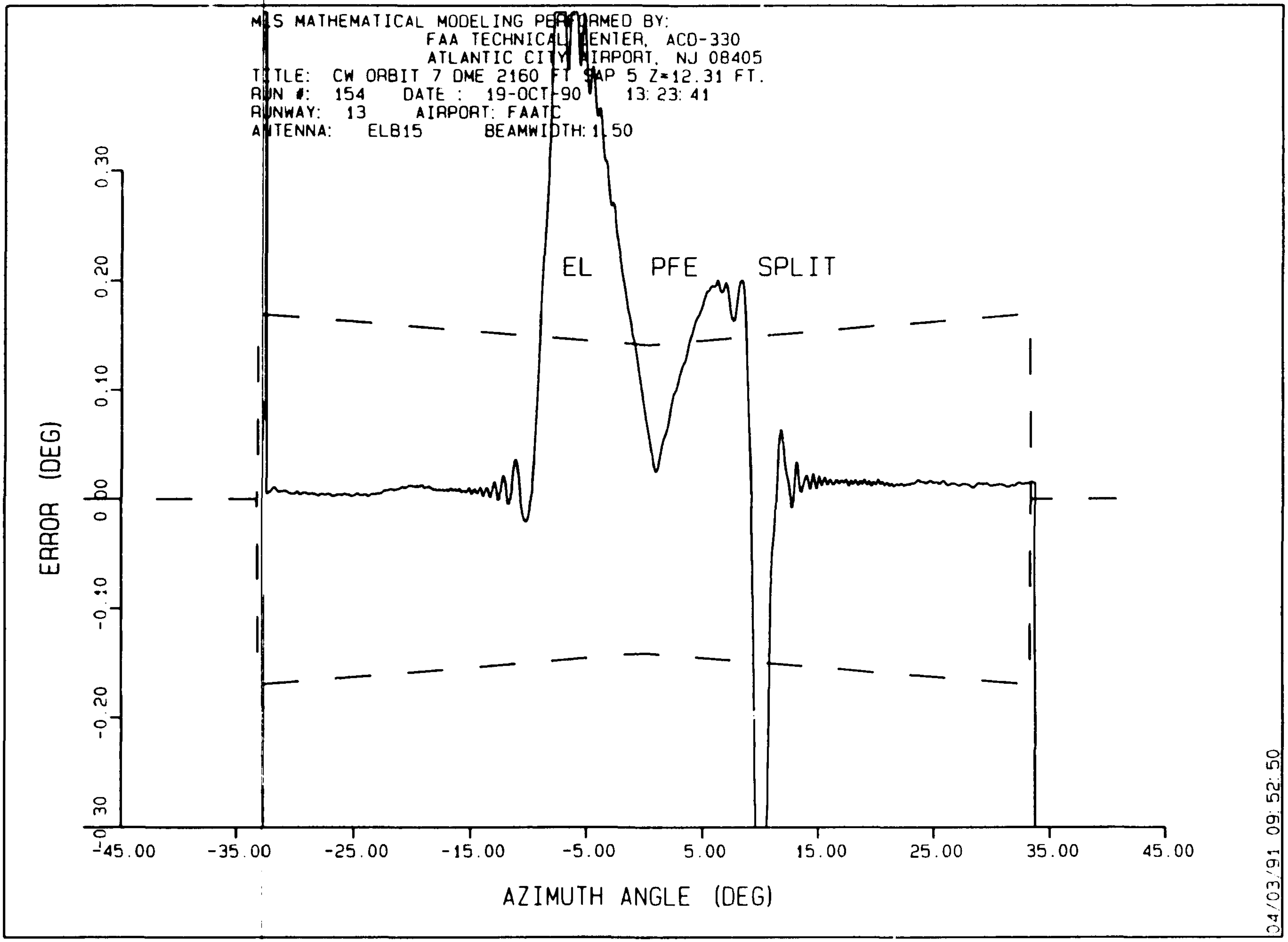

FIGURE 9. ORBIT AT 3.0 DEGREE ELEVATION ANGLE, 7 NMI FROM DME, ELEVATION SYSTEM, SHADOWING AIRCRAFT POSITION 5, MODEL PFE FILTERED PLOT

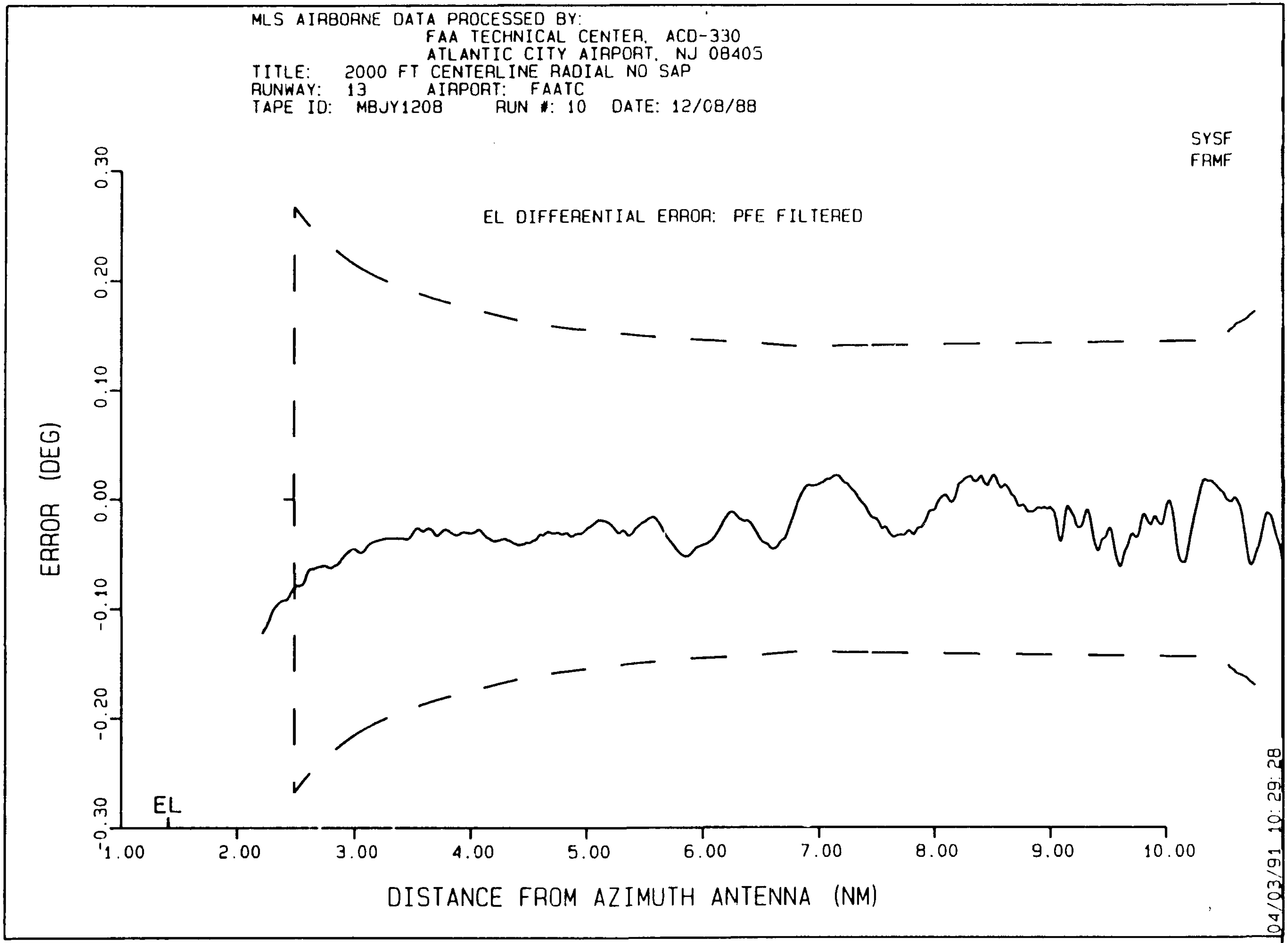

FIGURE 10. CENTERLINE RADIAL AT 2000 FEET, ELEVATION SYSTEM, NO SHADOWING AIRCRAFT, MEASURED ERROR PLOT

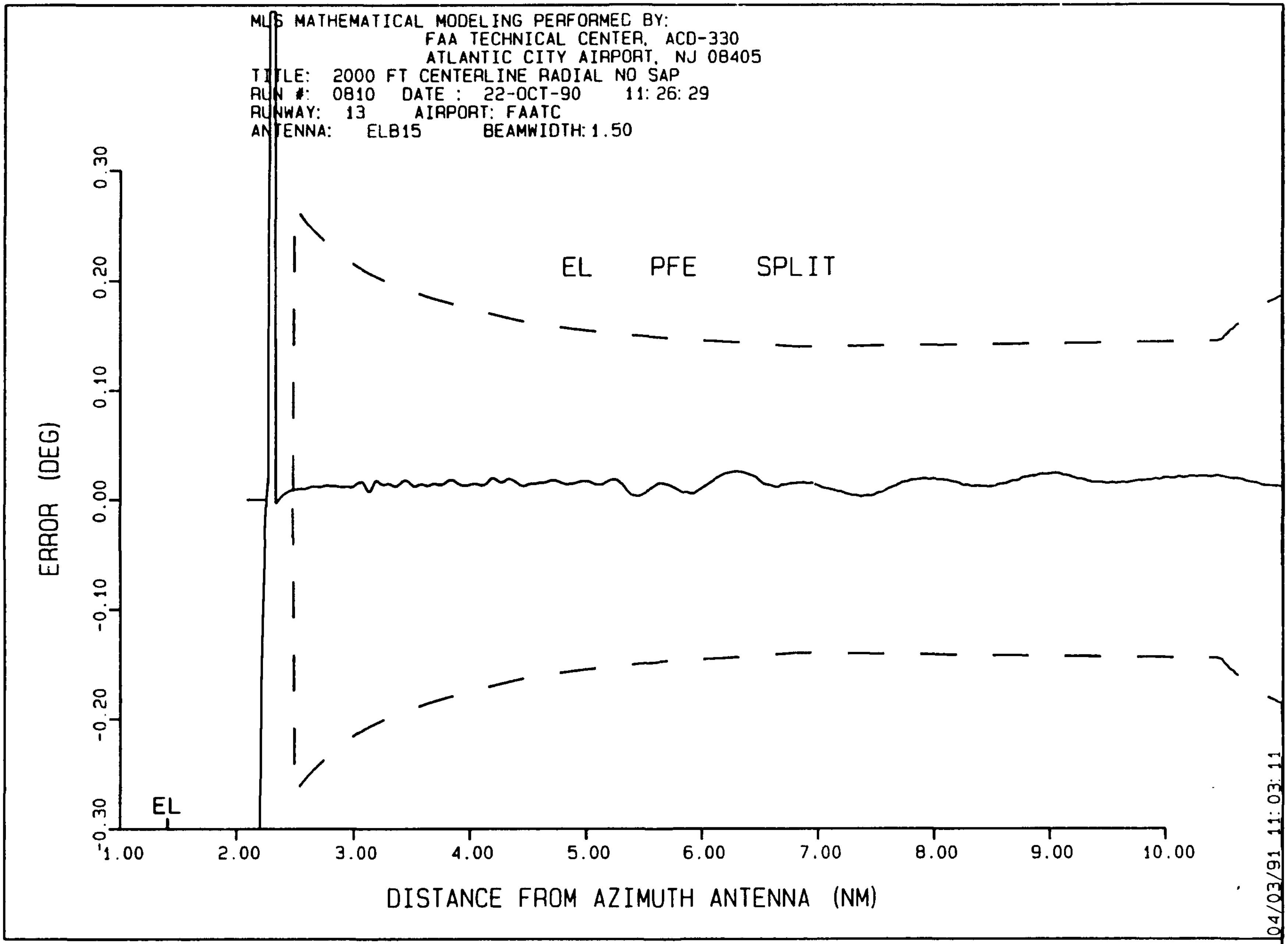

FIGURE 11. **CENTERLINE RADIAL AT 2000 FEET, ELEVATION SYSTEM, NO SHADOWING AIRCRAFT, MODEL PFE FILTERED PLOT, ELB15 ANTENNA PATTERN**

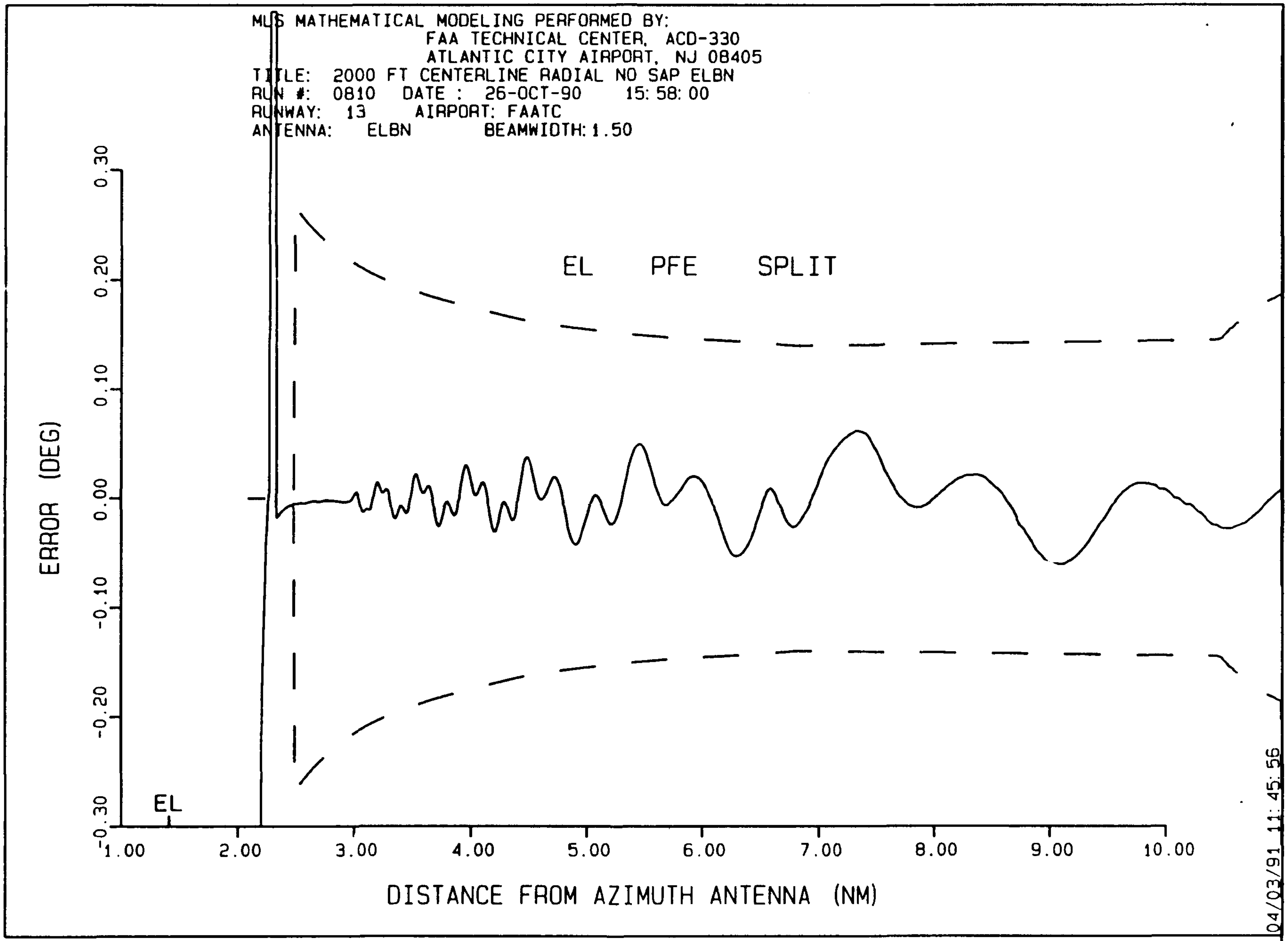

FIGURE 12. **CENTERLINE RADIAL AT 2000 FEET, ELEVATION SYSTEM, NO SHADOWING AIRCRAFT, MODEL PFE FILTERED PLOT, ELBN ANTENNA PATTERN**

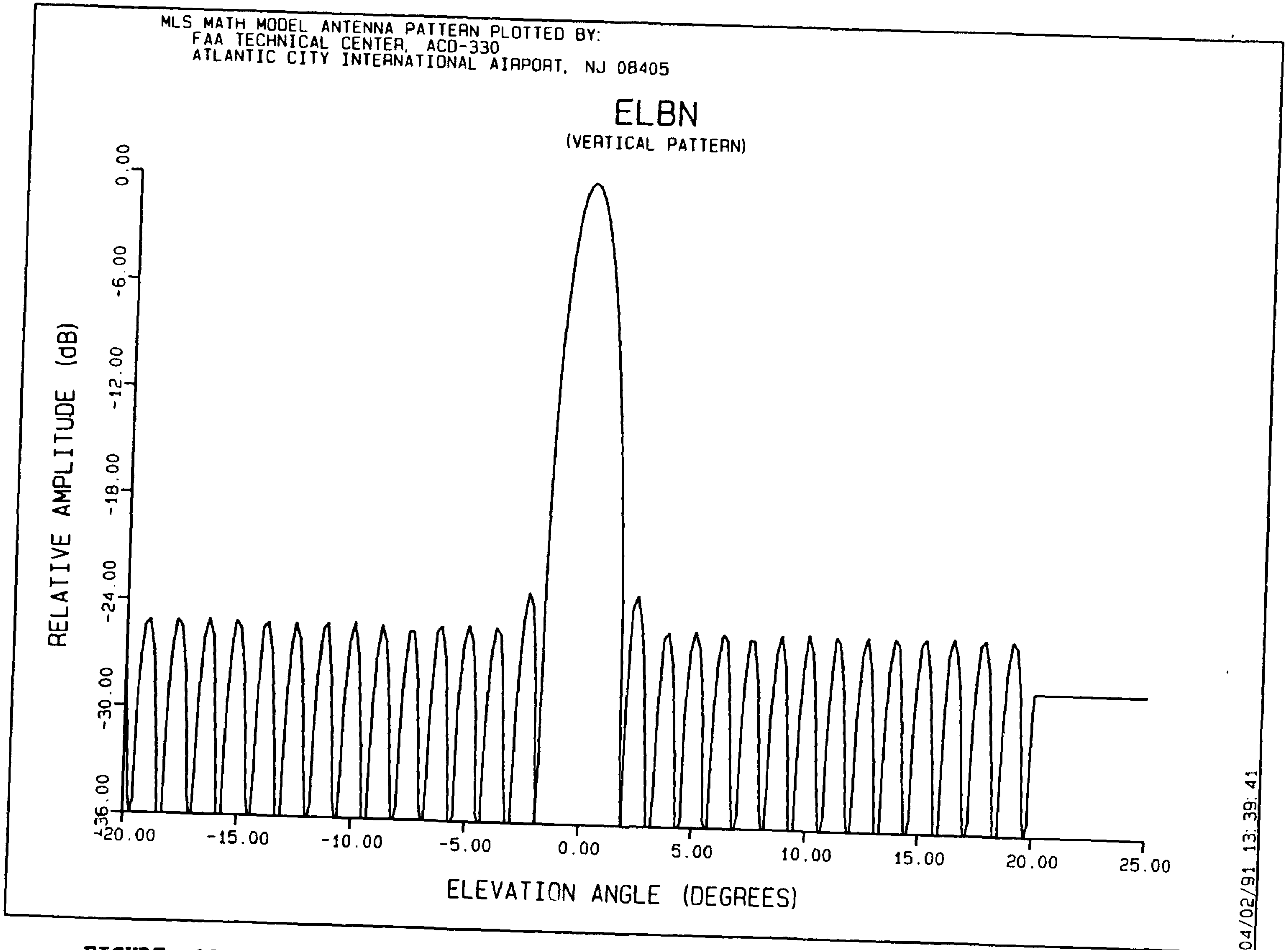

FIGURE 13. BASIC NARROW 1.5° ELEVATION ANTENNA (ELBN) VERTICAL RADIATION PATTERN INSTALLED IN THE MLS MATH MODEL

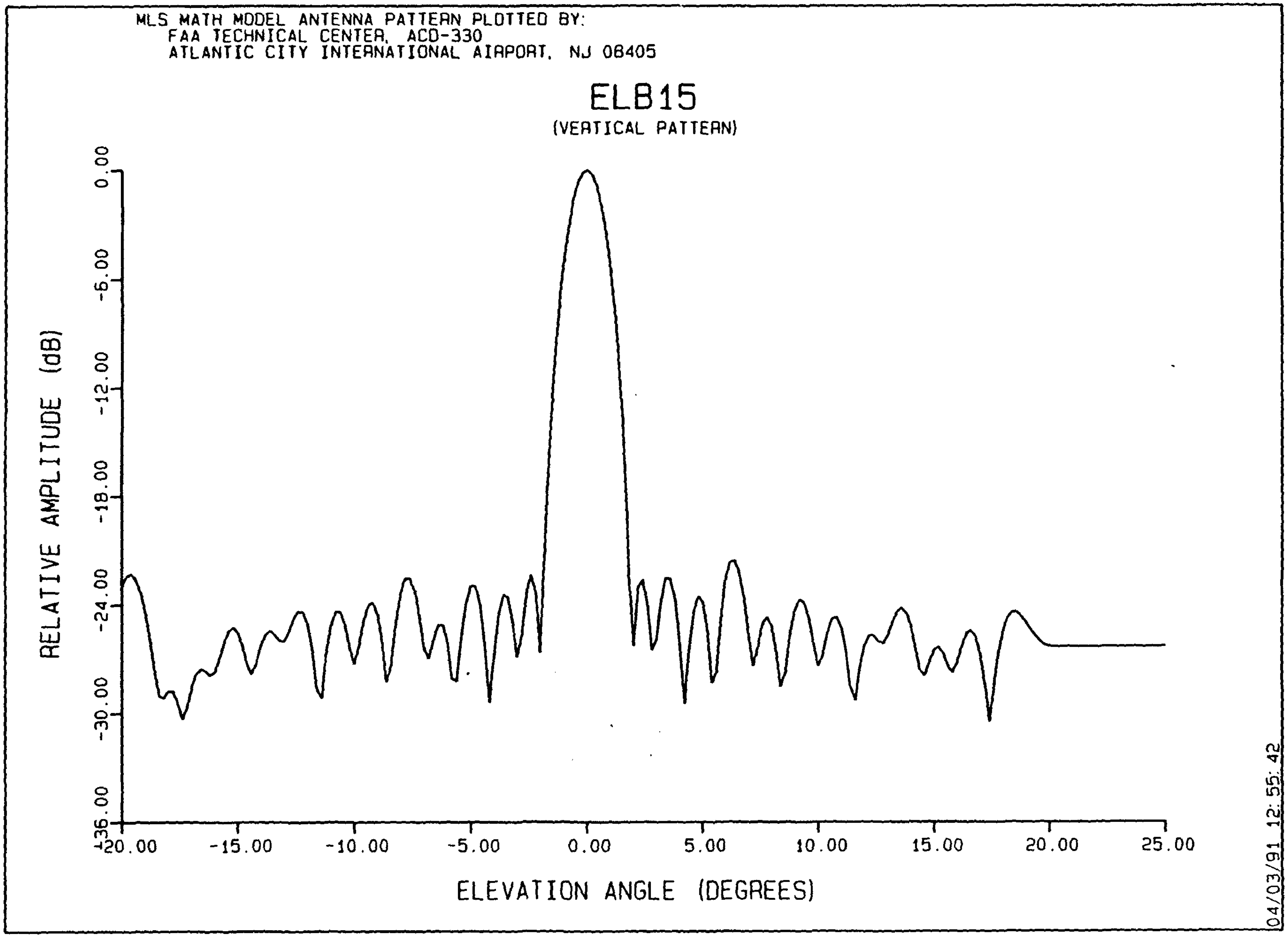

FIGURE 14. BENDIX TESTBED 1.5° ELEVATION ANTENNA (ELB15) VERTICAL RADIATION PATTERN INSTALLED IN THE MLS MATH MODEL

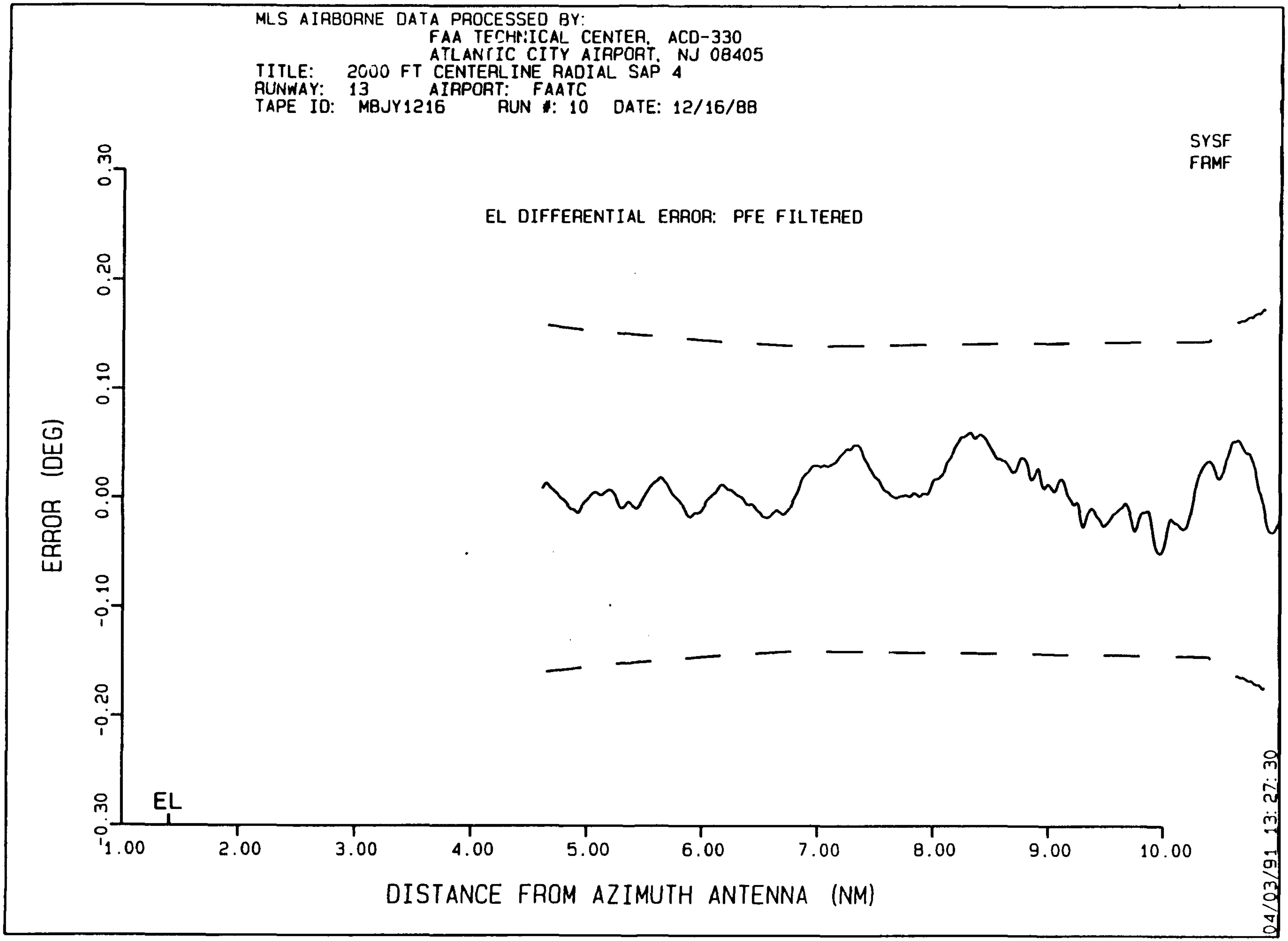

FIGURE 15. CENTERLINE RADIAL AT 2000 FEET, ELEVATION SYSTEM, SHADOWING AIRCRAFT POSITION 4, MEASURED ERROR PLOT

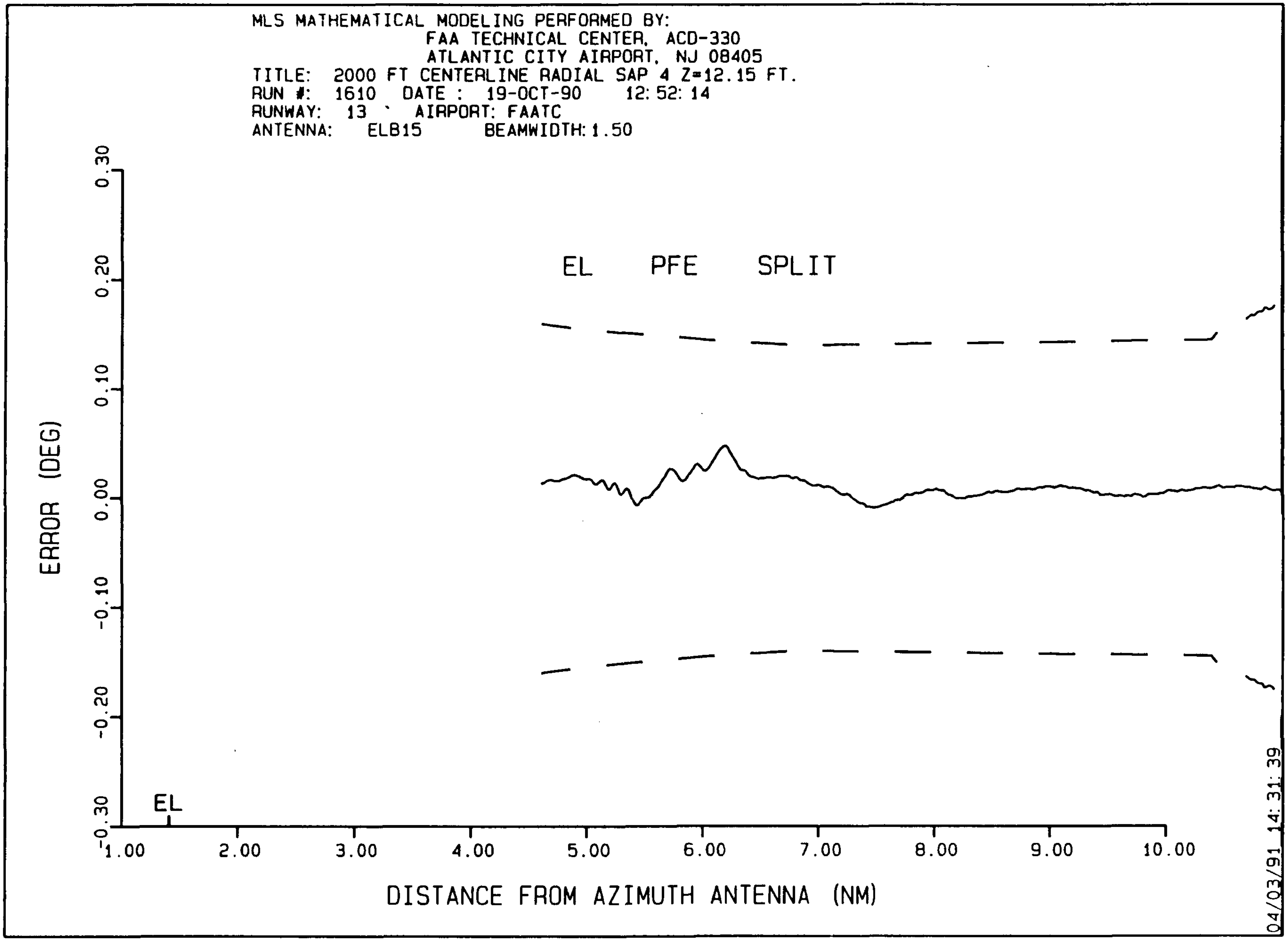

FIGURE 16. CENTERLINE RADIAL AT 2000 FEET, ELEVATION SYSTEM, SHADOWING AIRCRAFT POSITION 4, MODEL PFE FILTERED PLOT

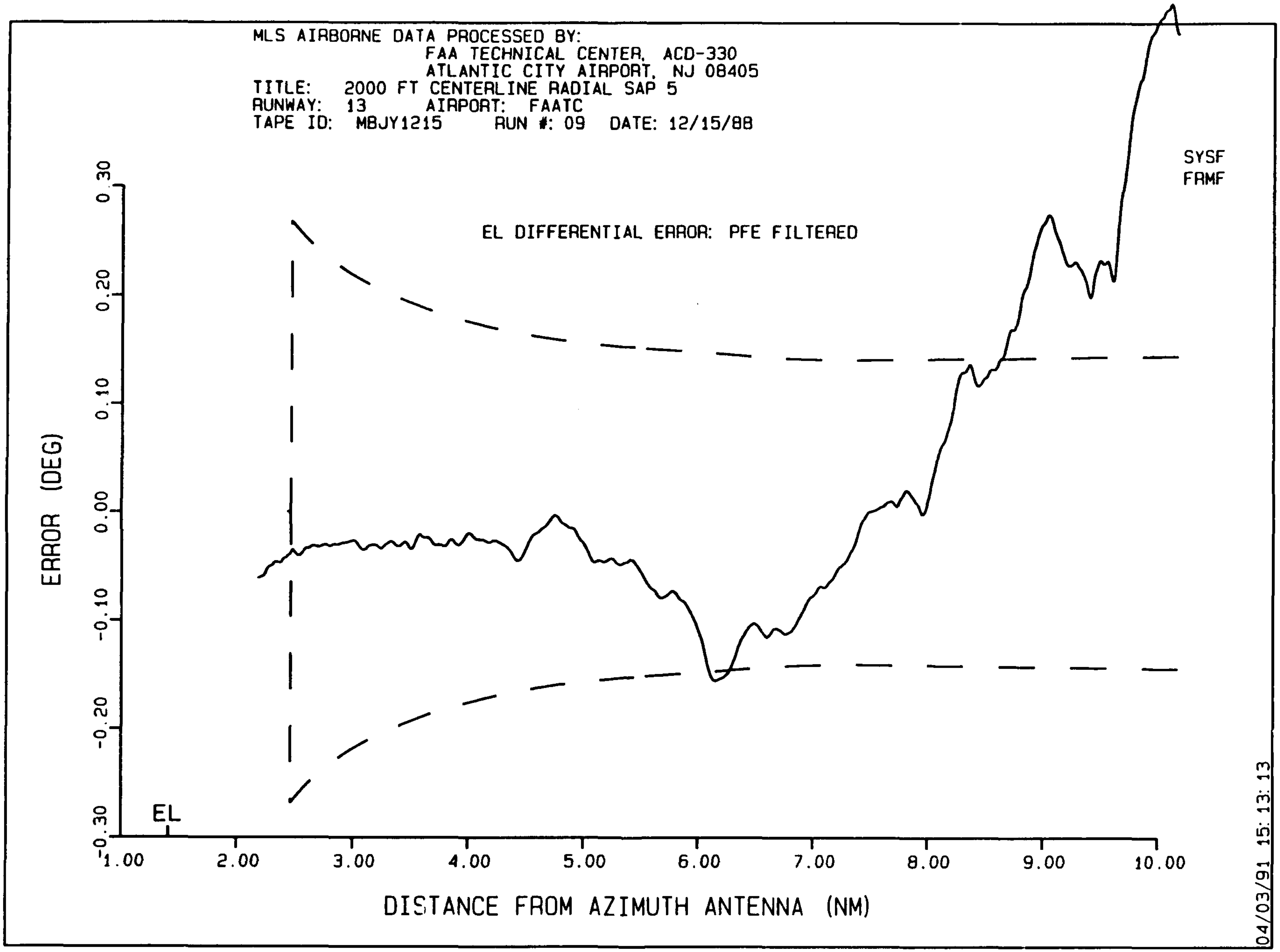

FIGURE 17. CENTERLINE RADIAL AT 2000 FEET, ELEVATION SYSTEM, SHADOWING AIRCRAFT POSITION 5, MEASURED ERROR PLOT

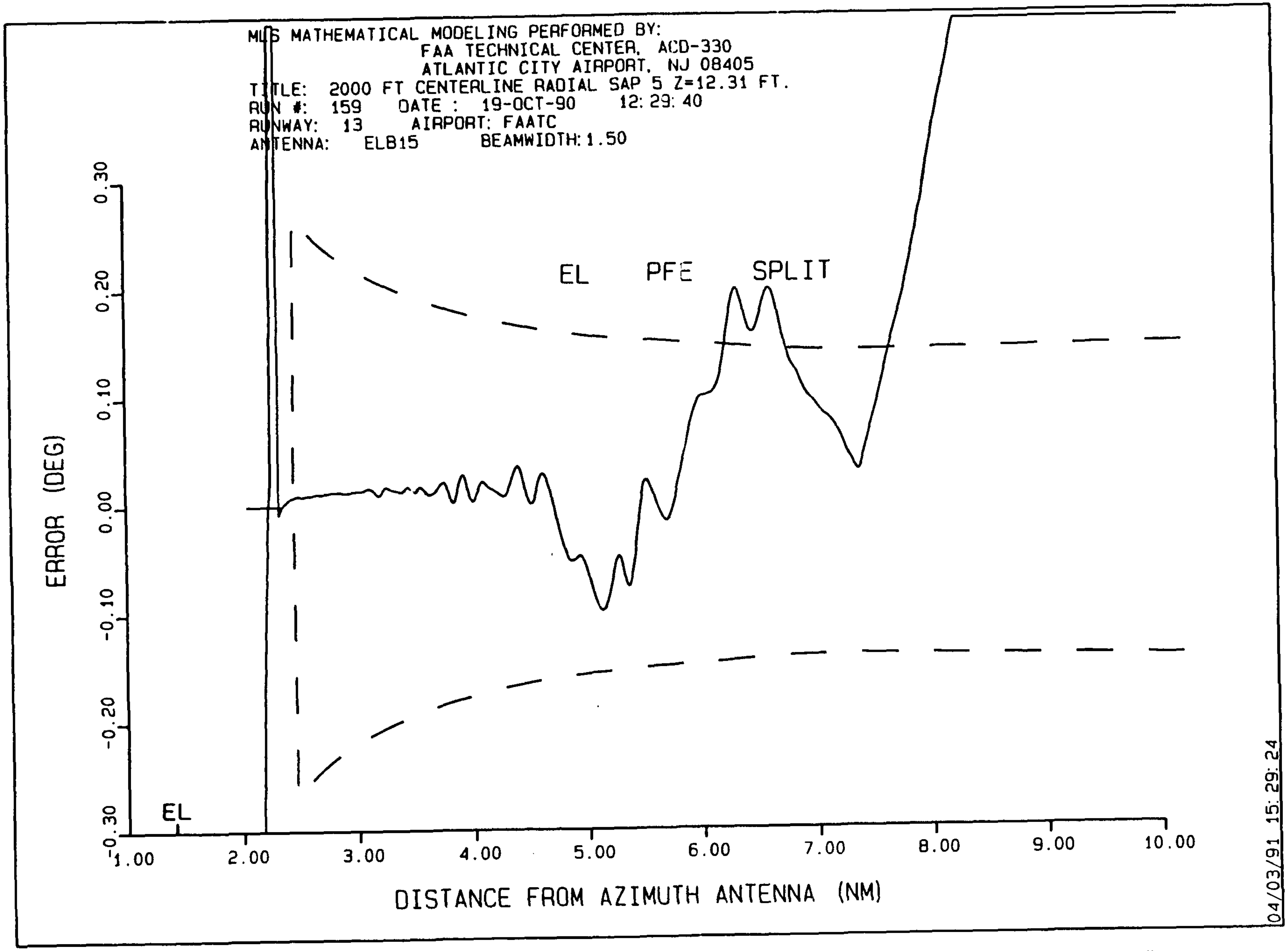

FIGURE 18. CENTERLINE RADIAL AT 2000 FEET, ELEVATION SYSTEM, SHADOWING AIRCRAFT POSITION 5, MODEL PFE FILTERED PLOT

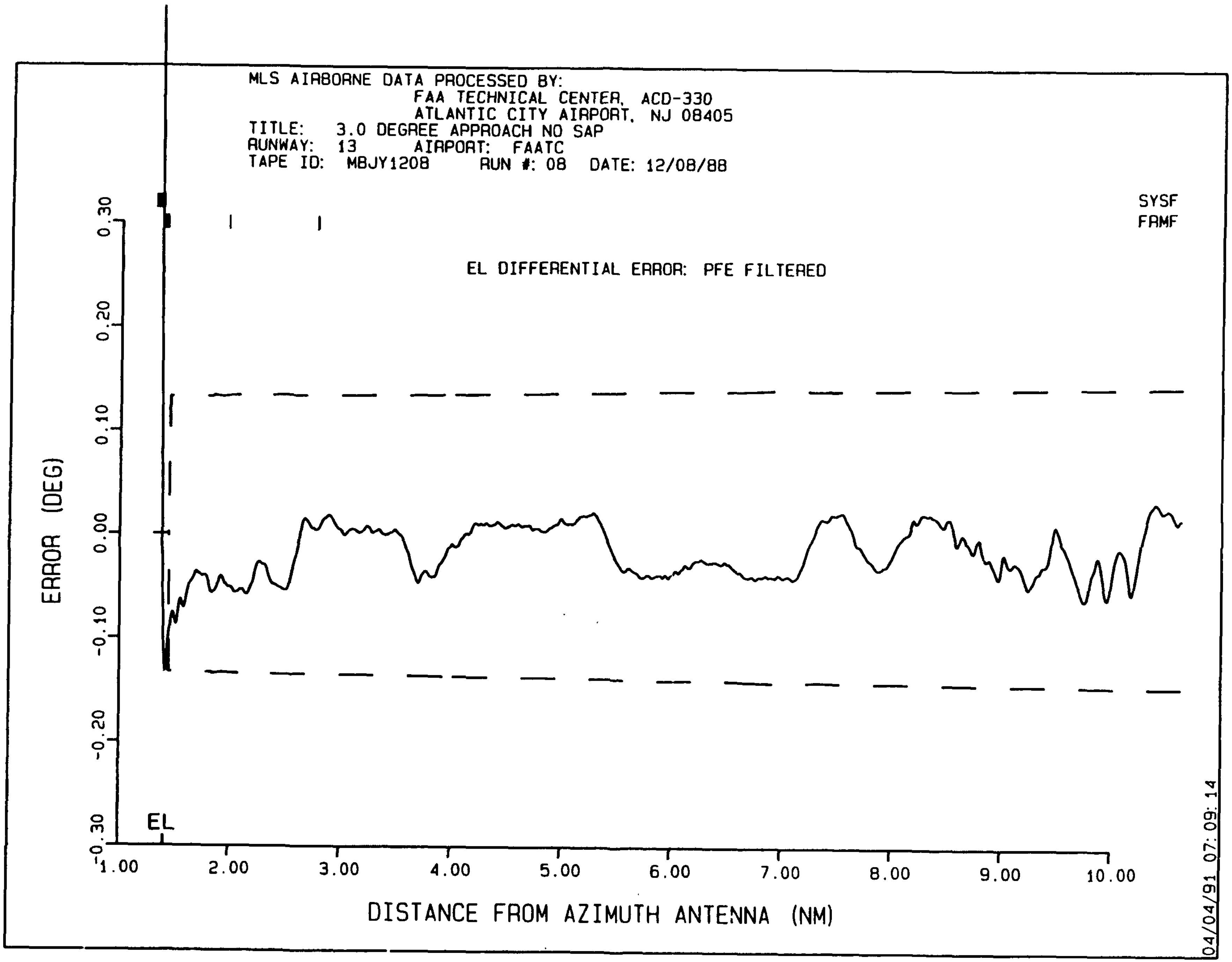

FIGURE 19. 3.0 DEGREE CENTERLINE APPROACH, ELEVATION SYSTEM, NO SHADOWING AIRCRAFT, MEASURED ERROR PLOT

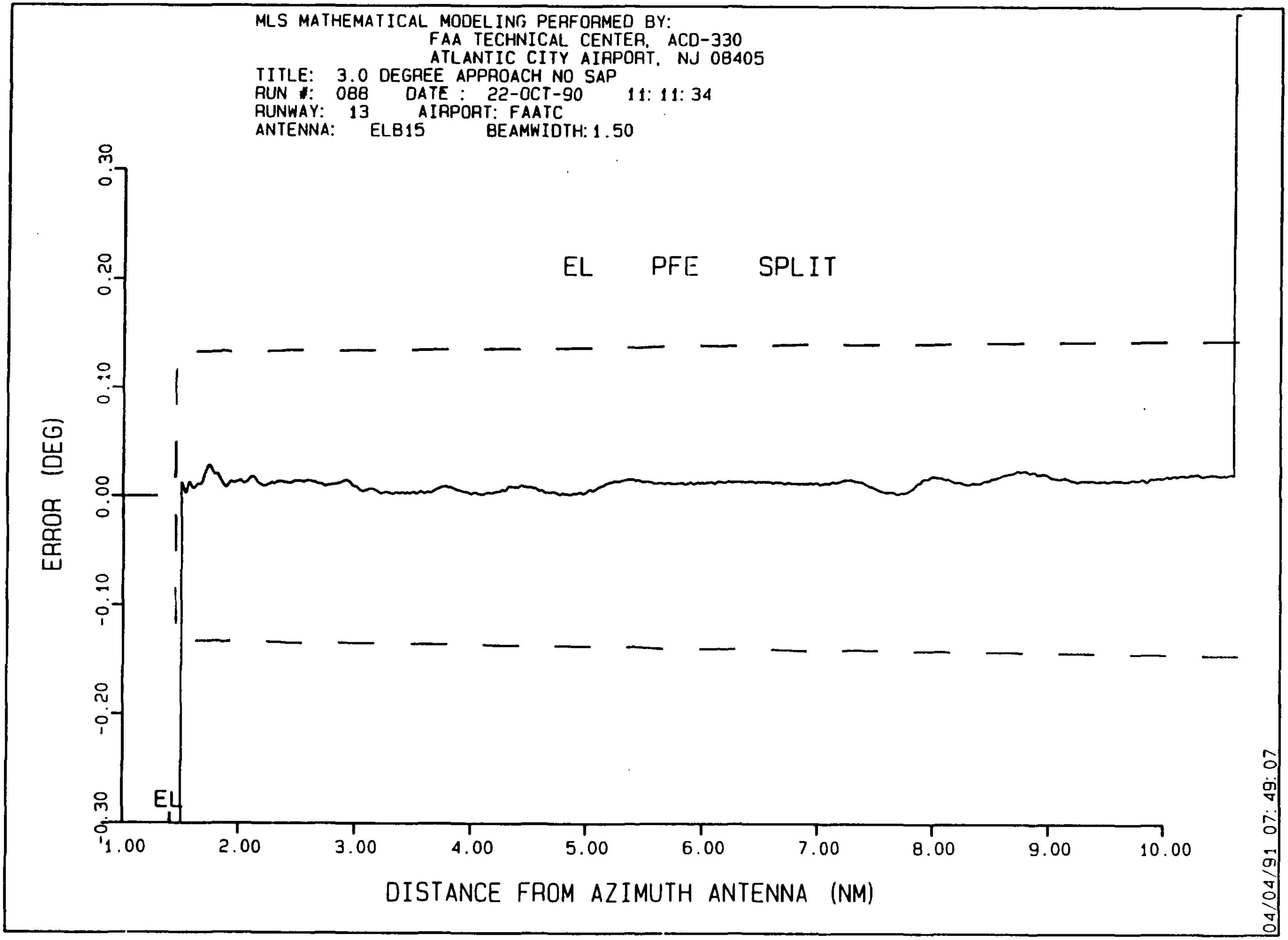

FIGURE 20. 3.0 DEGREE CENTERLINE APPROACH, ELEVATION SYSTEM, NO SHADOWING AIRCRAFT, MODEL PFE FILTERED PLOT

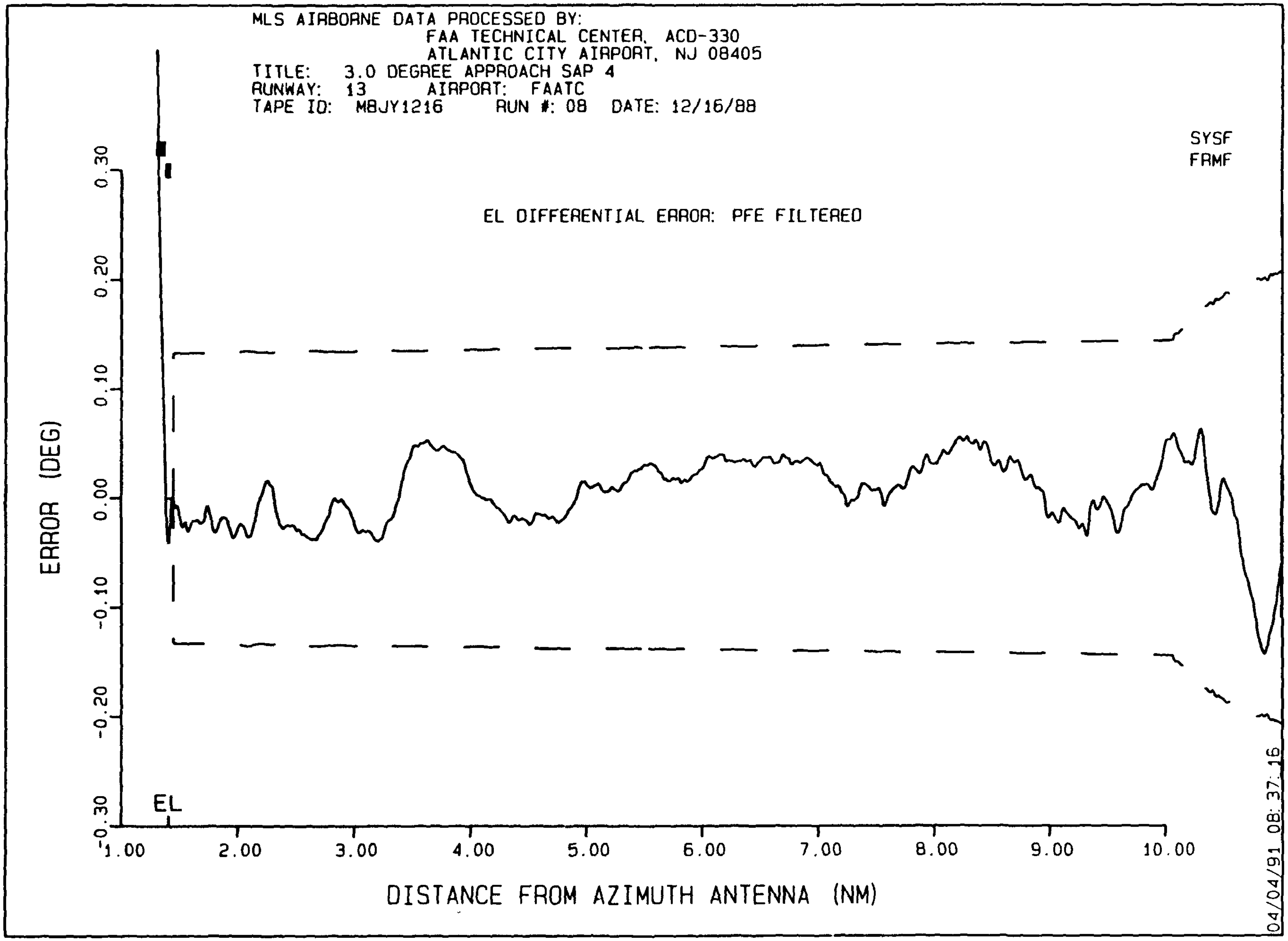

FIGURE 21. **3.0 DEGREE CENTERLINE APPROACH, ELEVATION SYSTEM, SHADOWING AIRCRAFT POSITION 4, MEASURED ERROR PLOT**

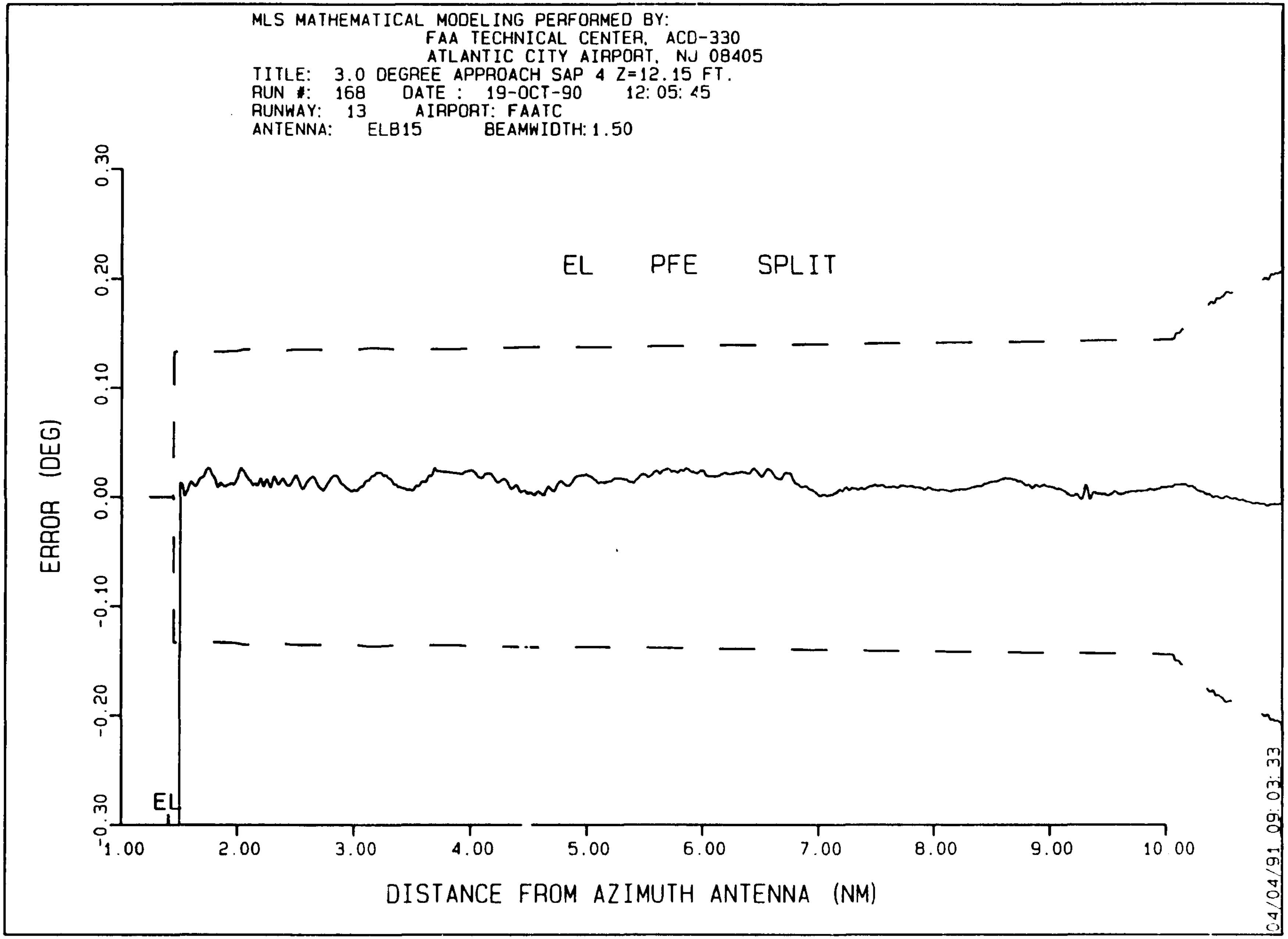

FIGURE 22. **3.0 DEGREE CENTERLINE APPROACH, ELEVATION SYSTEM, SHADOWING AIRCRAFT POSITION 4, MODEL PFE FILTERED PLOT**

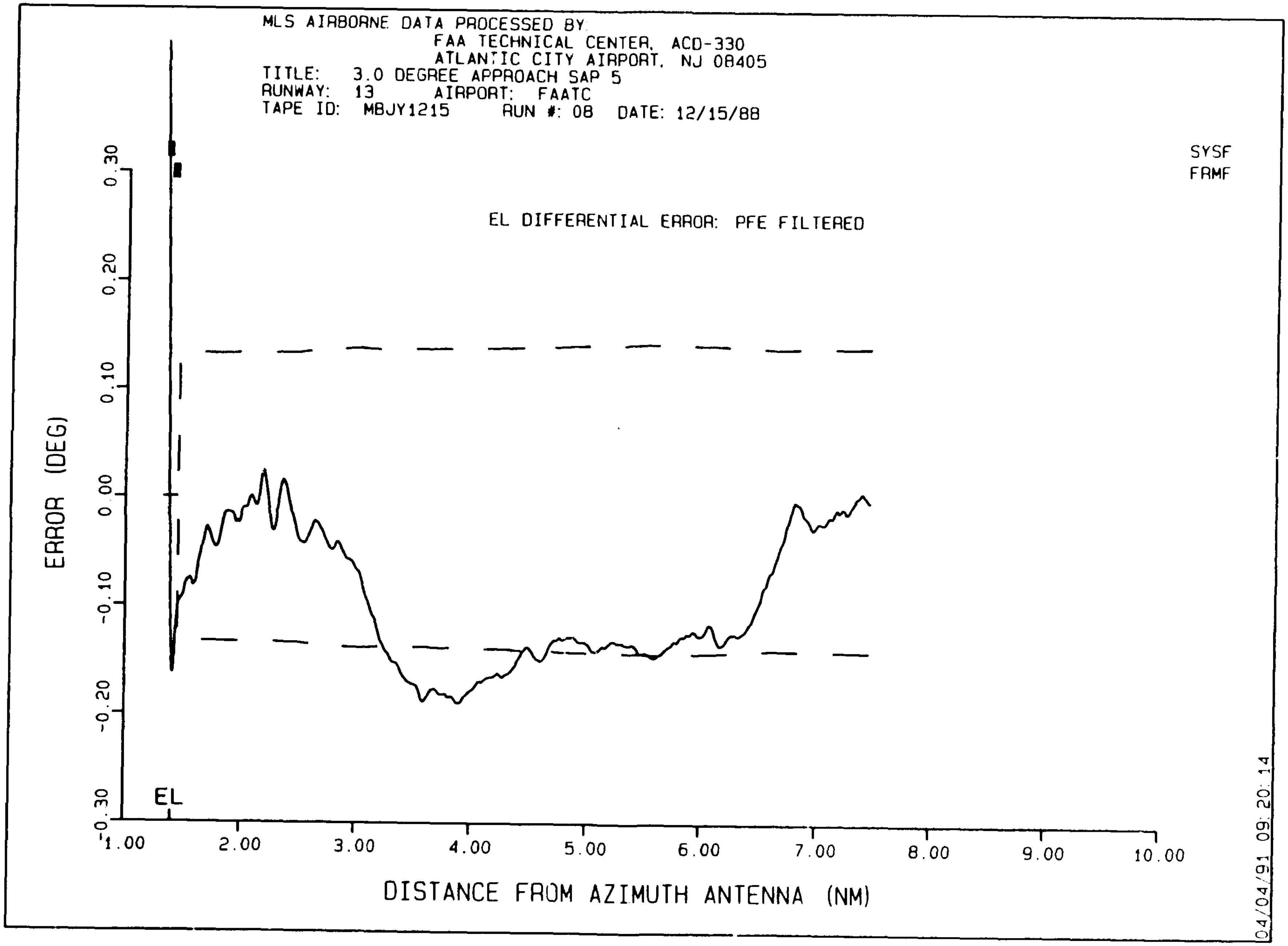

FIGURE 23. 3.0 DEGREE CENTERLINE APPROACH, ELEVATION SYSTEM, SHADOWING AIRCRAFT POSITION 5, MEASURED ERROR PLOT

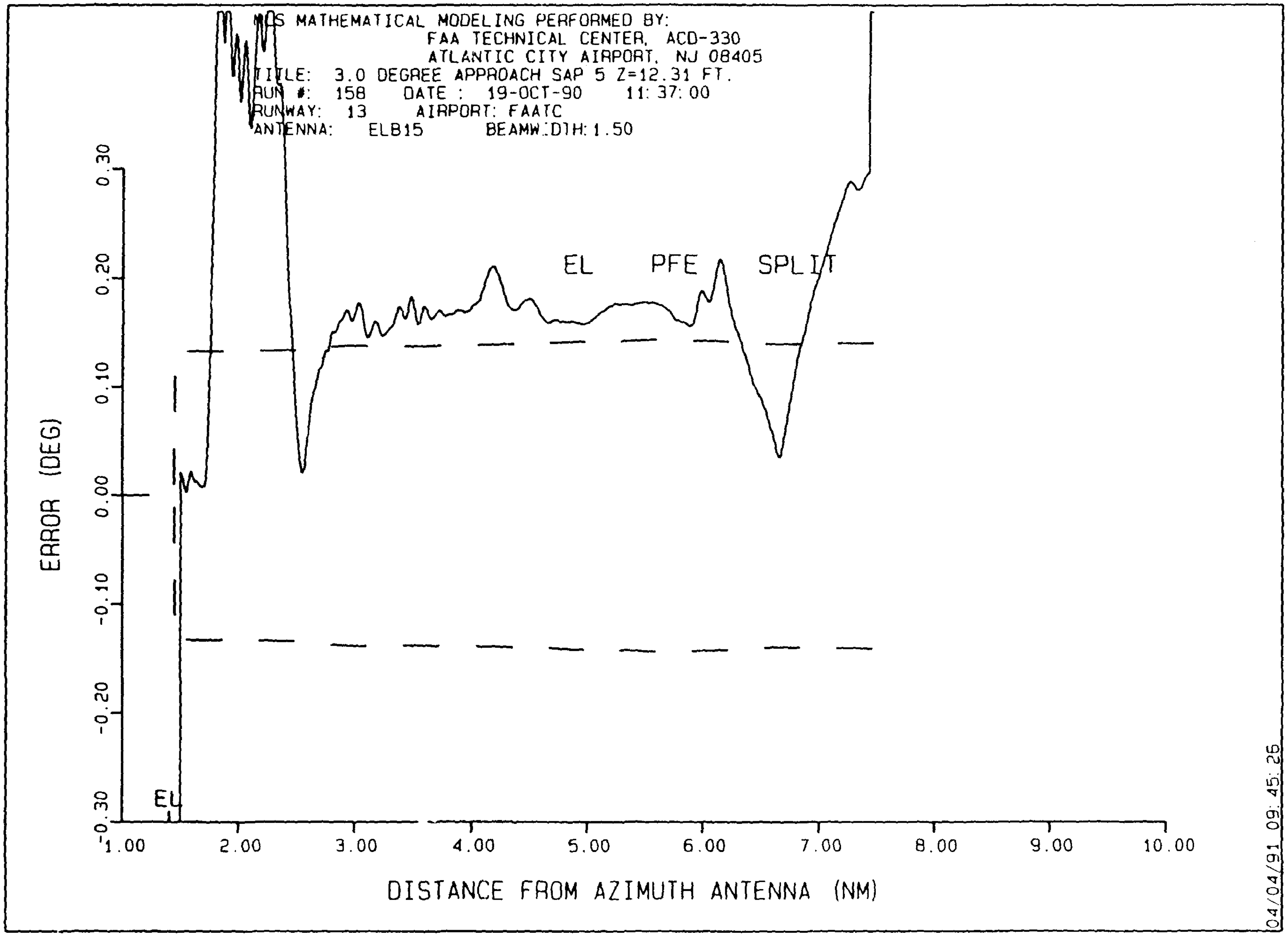

FIGURE 24. 3.0 DEGREE CENTERLINE APPROACH, ELEVATION SYSTEM, SHADOWING AIRCRAFT POSITION 5 (Z=12.31 FT), MODEL PFE FILTERED PLOT

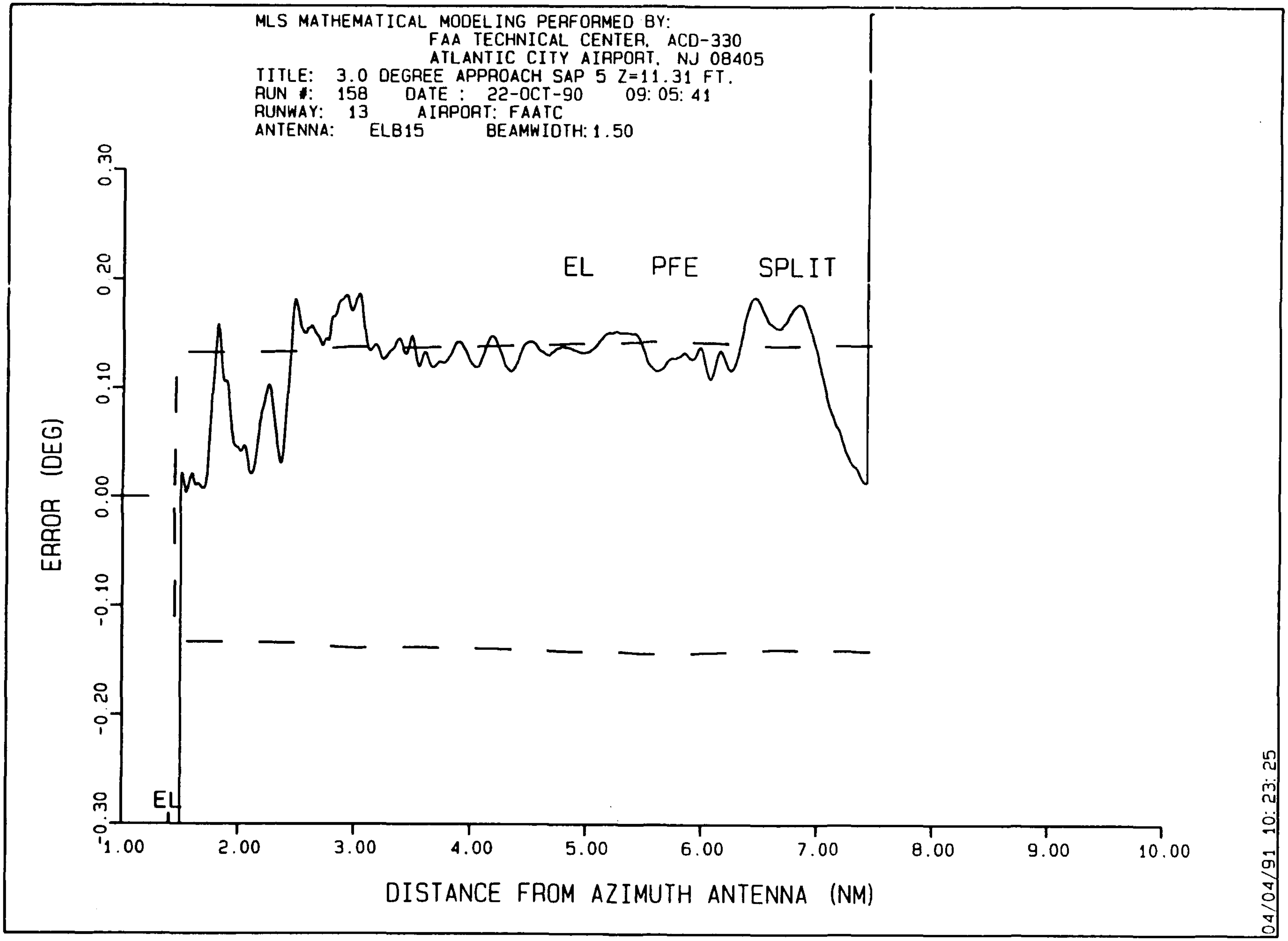

FIGURE 25. 3.0 DEGREE CENTERLINE APPROACH, ELEVATION SYSTEM, SHADOWING AIRCRAFT POSITION 5 (Z=11.31 FT), MODEL PFE FILTERED PLOT

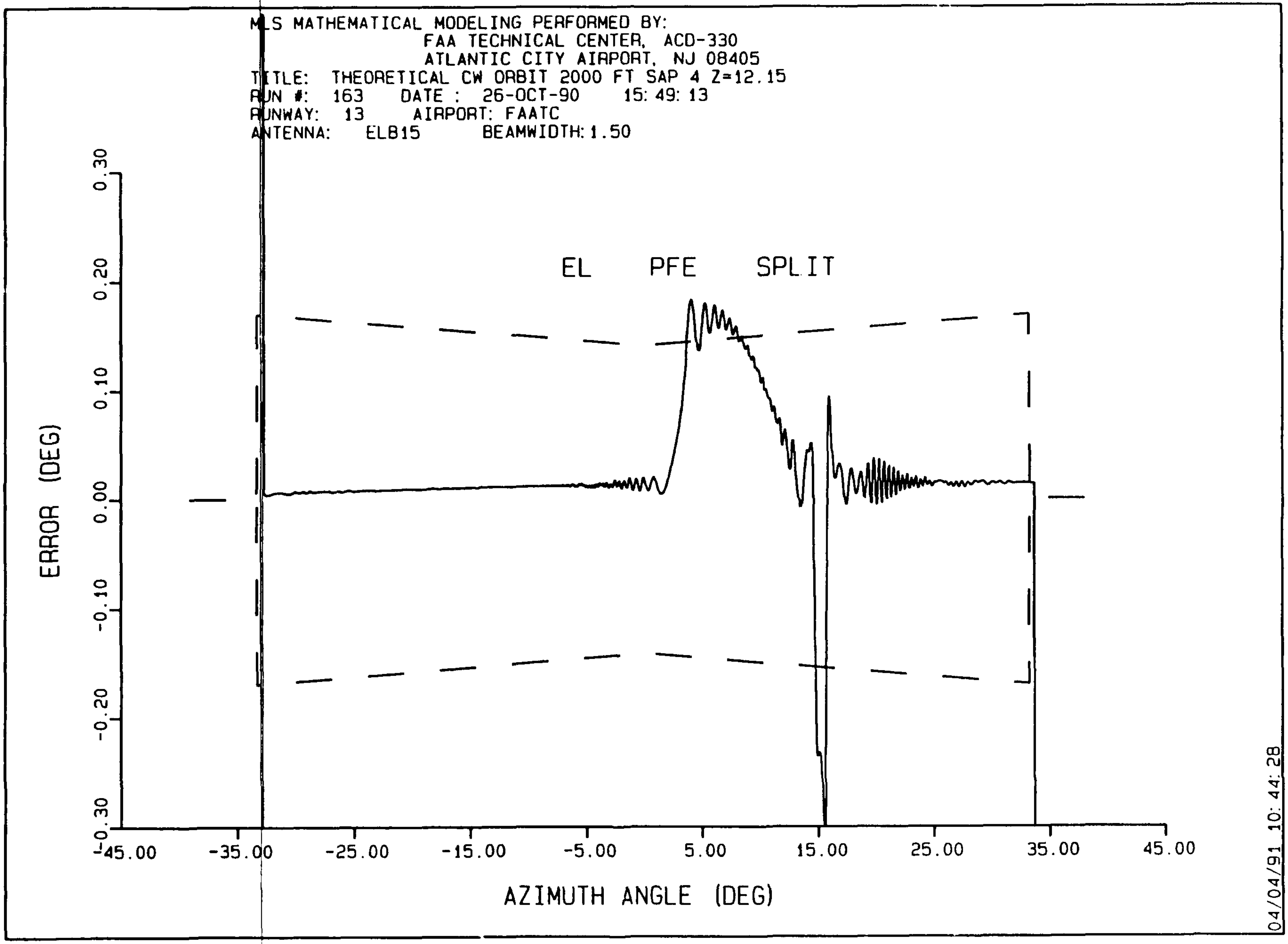

FIGURE 26. 2000-FOOT ORBIT WITH CALCULATED FLIGHTPATH

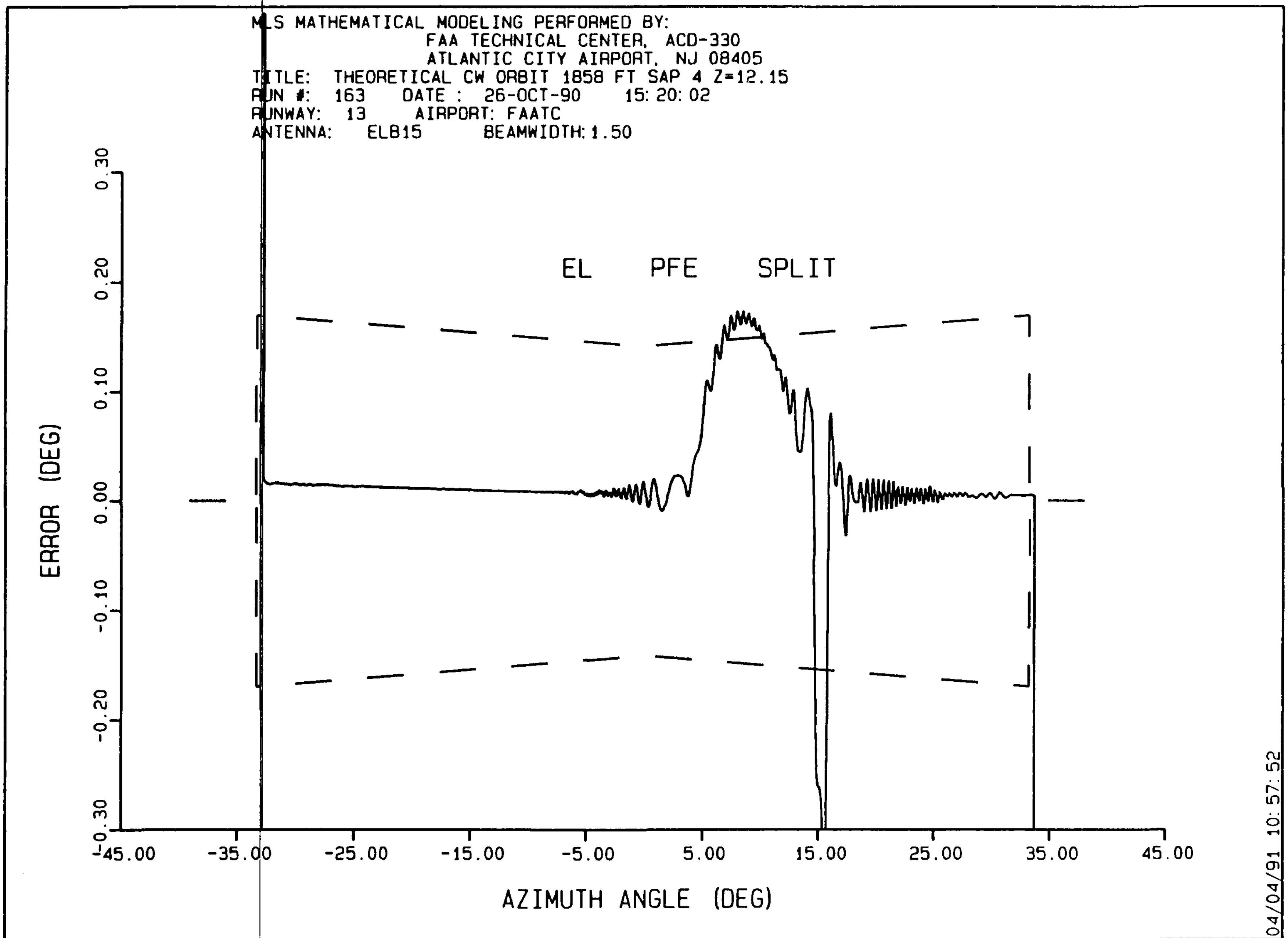

FIGURE 27. 1858-FOOT ORBIT WITH CALCULATED FLIGHTPATH

APPENDIX A

INPUT FILE FOR SHADOWING AIRCRAFT POSITION SAP4

```
********************MLS MATHEMATICAL MODEL INPUT DATA FILE************************
SECTION  0
          = SCENARIO DATA
          RUN ID# :1610
          TITLE   :2000 FT CENTERLINE RADIAL SAP 4 Z=12.15 FT.
          AIRPORT :FAATC
          RUNWAY  :13
          LENGTH  :10000
          WIDTH   :180
          ARDH    :55
          MGPA    :3.0
          UNITS   :FEET   (feet, meter) FOR ENTRIES IN FILE
SECTION  1
          = TRANSMITTER DATA
          PHASE CENTER:  X          Y         Z     FREQ(mhz)  LSL   USL    TYPE
                      --------  --------  --------  ---------  ----- ----- --------
          AZIMUTH  : -1184.27     -0.24     10.28     5061.0 -40.0  40.0 AZBR2040
          ELEVATION:  7370.04   -490.92      9.04     5061.0   0.0  20.0 ELB15
          DME/P    :  4902.36    749.25     14.45      997.0   0.0 360.0 DMBN
          DME/P PUL: cos/cos2 cos/cos2 (gaussian for IA; cos/cos2 for FA mode)
          DME/P TYP: cos/cos2
SECTION  2
          YES - DO ANY GROUND REFLECTION PROCESSING (CALL GREFC) (yes,no)
          YES - DO FULL INTEGRATION FOR SPECULAR GROUND SCATTERING (yes,no)
          = DEFAULT DIELECTRIC CONSTANT AND ROUGHNESS HEIGHT
          DIELECTRIC CONSTANT : 1.2        0.0
          ROUGHNESS HEIGHT    : 0.06
         * FOR MULTIPLE SCATTERING PATHS FROM AIRCRAFT AND BUILDINGS
          DIELECTRIC CONSTANT : 1.2        0.0
          ROUGHNESS HEIGHT    : 0.06
SECTION  4
          = SCATTERING FROM BUILDINGS (MAXIMUM OF 10)
          yes - RUN SCATTERING BUILDINGS (yes,no)
       ##  X-LEFT   Y-LEFT   X-RGHT   Y-RGHT   ELV   HGT   TLT   GRCORR   CMP
       -- -------- -------- -------- -------- ----- ----- ----- -------- -----
       nn xxxxxxxx yyyyyyyy xxxxxxxx yyyyyyyy eeeee hhhhh ttttt cccccccc mmmmm
       01   9130.0    760.0   9190.0    760.0  10.4  10.0   0.0      0.0 METAL
SECTION  5
          = SPECULAR SCATTERING FROM RECTANGULAR GROUND SURFACES (MAX OF 10)
          yes - RUN RECTANGULAR GROUND (yes,no)
          THIS SECTION MAY BE SKIPPED DEPENDING ON ANSWERS IN SECTION 2
       ##  X-VALU   Y-VALU   Z-VALU   DCREAL   DCIMAG   ROUGHN  SF
       -- -------- -------- -------- -------- -------- -------- --
       nn x1x1x1x1 y1y1y1y1 z1z1z1z1 rrrrrrrr iiiiiiii rrrrrrrr is
          x2x2x2x2 y2y2y2y2 z2z2z2z2
          x3x3x3x3 y3y3y3y3 z3z3z3z3
       01  7254.99  -239.26     3.24     10.0     -9.0     0.00 01
           7308.48  -186.08     3.84
           7943.41  -814.14     4.57
       02  7308.48  -186.08     3.84     10.0     -9.0     0.00 01
           7361.97  -132.90     3.64
           7994.16  -763.24     1.54
       03  7931.17  -135.04     3.44     10.0     -9.0     0.00 01
           7999.28  -134.85     2.84
           8000.89  -134.85     2.84
SECTION  8
          = SHADOWING BY AIRCRAFT
          YES - RUN SHADOWING AIRCRAFT (yes,no)
       ##  X-VALU   Y-VALU   Z-VALU   VEL   ANG   AT
       -- -------- -------- -------- ----- ----- --
       nn sax1sax1 say1say1 saz1saz1 vvvvv aaaaa tt
          sax2sax2 say2say2 saz2saz2
       05   7641.7   -581.0    12.15   0.0   0.0 03
            7639.7   -579.0    12.15
```

```
SECTION  9
            = SHADOWING BY BUILDINGS
            yes - RUN SHADOWING BUILDINGS (yes,no)
        ##  X-LEFT   Y-LEFT   X-RGHT   Y-RGHT   ELV   HGT
        -- -------- -------- -------- -------- ----- -----
        nn xxxxxxxx yyyyyyyy xxxxxxxx yyyyyyyy eeeee hhhhh
        01   8857.0   -400.0   8857.0   -412.0   4.4   8.0
        02   8572.0   -445.0   8572.0   -463.0   4.4   6.0
SECTION 12
            = FLIGHT PATH
            FAF       : 6.242  NAUTICAL MILES
            DATUM     : 7370.04    0.0    6.28
            TYPE      : MEASURED   (distance,measured,segmented,straight,
          *                            radial,orbit)
            VELOCITY :    200.0
            INCREMENT:     40.0
            DATA RATE:      0.2
          *  IF "straight" SUFFICIENT DATA IS AVAILABLE TO COMPUTE FLIGHT PATH
          *  IF "radial" ENTER ANGLE,ELEVATION & STARTING AND ENDING DISTANCES
          *               (nm from dme/p)
            ANGLE: aaaaaaaa
            SDIST: dddddddd
            EDIST: dddddddd
            ELEV : eeeeeeee
          *  IF "orbit" ENTER RADIUS (nm from dme/p) & ELEVATION
            RADIUS: rrrrrrrr
            ELEV  : eeeeeeee  (m.s.l.)
          *  IF "measured" X,Y,Z COORDINATES AND TIME WILL BE READ FROM UNIT 15
          *      WITH VELOCITY AND DATA INCREMENT COMPUTED FROM INPUT
          *  IF "segmented" or "distance" ENTER SEGMENT #,X,Y,Z,VELOCITY AND
          *      INCREMENT
        ##    XS       YS       ZS      VEL      INC
        -- -------- -------- -------- -------- --------
        nn xxxxxxxx yyyyyyyy zzzzzzzz vvvvvvvv iiiiiiii
SECTION 13
            = PLOT SCALE LIMITS
          * FLIGHT PATH PLOTS:
                                  X/Y PLOT     X/Z PLOT     D/Z PLOT
                                 ----------   ----------   ----------
              MINIMUM X VALUE :  -2000.0 ft   -2000.0 ft       0.0 ft
              UNITS PER INCH  :   6000.0 ft    6000.0 ft    6000.0 ft
              MINIMUM Y VALUE :  -3000.0 ft    -500.0 ft    -500.0 ft
              UNITS PER INCH  :   1000.0 ft     500.0 ft     500.0 ft
          * AIRPORT LAYOUT PLOT:
                                  X/Y PLOT
                                 ----------
              MINIMUM X VALUE :  -2000.0 ft
              UNITS PER INCH  :   2000.0 ft
              MINIMUM Y VALUE :  -6000.0 ft
              UNITS PER INCH  :   2000.0 ft
          * MULTIPATH DIAGNOSTIC PLOTS:
                                   M/D         SEP ANG     TIM DELAY    SHADOWING
                                 ---------   ---------    ---------    ---------
              MINIMUM X VALUE :    1.0 nm      1.0 nm       1.0 nm       1.0 nm
              UNITS PER INCH  :    1.5 nm      1.5 nm       1.5 nm       1.5 nm
              MINIMUM Y VALUE :  -25.0 db    -15.0 deg      0.0 ns     -25.0 db
              UNITS PER INCH  :    5.0 db      5.0 deg    200.0 ns       5.0 db
          * RECEIVER OUTPUT ERROR & FILTERED ERROR PLOTS:
                                   RAW         PFE          CMN
                                 ---------   ---------    ---------
              MINIMUM X VALUE :    1.0 nm      1.0 nm       1.0 nm
              UNITS PER INCH  :    1.0 nm      1.0 nm       1.0 nm
              MINIMUM Y VALUE :  -0.30 deg   -0.30 deg    -0.30 deg
              UNITS PER INCH  :   0.10 deg    0.10 deg     0.10 deg
END DATA
```

APPENDIX B

INPUT FILE FOR SHADOWING AIRCRAFT POSITION SAP5

```
*******************MLS MATHEMATICAL MODEL INPUT DATA FILE***********************
SECTION  0
          = SCENARIO DATA
          RUN ID# :159
          TITLE   :2000 FT CENTERLINE RADIAL SAP 5 Z=12.31 FT.
          AIRPORT :FAATC
          RUNWAY  :13
          LENGTH  :10000
          WIDTH   :180
          ARDH    :55
          MGPA    :3.0
          UNITS   :FEET   (feet, meter) FOR ENTRIES IN FILE
SECTION  1
          = TRANSMITTER DATA
          PHASE CENTER:  X         Y         Z     FREQ(mhz)  LSL   USL    TYPE
                     -------- -------- -------- --------- ----- ----- --------
          AZIMUTH  : -1184.27    -0.24    10.28    5061.0 -40.0  40.0 AZBR2040
          ELEVATION:  7370.04  -490.92     9.04    5061.0   0.0  20.0 ELB15
          DME/P    :  4902.36   749.25    14.45     997.0   0.0 360.0 DMBN
          DME/P PUL: cos/cos2 cos/cos2 (gaussian for IA; cos/cos2 for FA mode)
          DME/P TYP: cos/cos2
SECTION  2
          YES - DO ANY GROUND REFLECTION PROCESSING (CALL GREFC) (yes,no)
          YES - DO FULL INTEGRATION FOR SPECULAR GROUND SCATTERING (yes,no)
          = DEFAULT DIELECTRIC CONSTANT AND ROUGHNESS HEIGHT
          DIELECTRIC CONSTANT : 1.2       0.0
          ROUGHNESS HEIGHT    : 0.06
         * FOR MULTIPLE SCATTERING PATHS FROM AIRCRAFT AND BUILDINGS
          DIELECTRIC CONSTANT : 1.2       0.0
          ROUGHNESS HEIGHT    : 0.06
SECTION  4
          = SCATTERING FROM BUILDINGS (MAXIMUM OF 10)
          yes - RUN SCATTERING BUILDINGS (yes,no)
       ## X-LEFT   Y-LEFT   X-RGHT   Y-RGHT   ELV   HGT   TLT   GRCORR   CMP
       -- -------- -------- -------- -------- ----- ----- ----- -------- -----
       nn xxxxxxxx yyyyyyyy xxxxxxxx yyyyyyyy eeeee hhhhh ttttt cccccccc mmmmm
       01   9130.0    760.0   9190.0    760.0  10.4  10.0   0.0      0.0 METAL
SECTION  5
          = SPECULAR SCATTERING FROM RECTANGULAR GROUND SURFACES (MAX OF 10)
          yes - RUN RECTANGULAR GROUND (yes,no)
          THIS SECTION MAY BE SKIPPED DEPENDING ON ANSWERS IN SECTION 2
       ## X-VALU   Y-VALU   Z-VALU   DCREAL   DCIMAG   ROUGHN   SF
       -- -------- -------- -------- -------- -------- -------- --
       nn x1x1x1x1 y1y1y1y1 z1z1z1z1 rrrrrrrr iiiiiiii rrrrrrrr is
          x2x2x2x2 y2y2y2y2 z2z2z2z2
          x3x3x3x3 y3y3y3y3 z3z3z3z3
       01  7254.99  -239.26     3.24     10.0     -9.0     0.00 01
           7308.48  -186.08     3.84
           7943.41  -814.14     4.57
       02  7308.48  -186.08     3.84     10.0     -9.0     0.00 01
           7361.97  -132.90     3.64
           7994.16  -763.24     1.54
       03  7931.17  -135.04     3.44     10.0     -9.0     0.00 01
           7999.28  -134.85     2.84
           8000.89  -134.85     2.84
SECTION  8
          = SHADOWING BY AIRCRAFT
          YES - RUN SHADOWING AIRCRAFT (yes,no)
       ## X-VALU   Y-VALU   Z-VALU   VEL   ANG   AT
       -- -------- -------- -------- ----- ----- --
       nn sax1sax1 say1say1 saz1saz1 vvvvv aaaaa tt
          sax2sax2 say2say2 saz2saz2
       05   7601.7   -541.0    12.31   0.0   0.0 03
            7599.7   -539.0    12.31
```

```
SECTION  9
           = SHADOWING BY BUILDINGS
           yes - RUN SHADOWING BUILDINGS (yes,no)
        ##  X-LEFT   Y-LEFT   X-RGHT   Y-RGHT   ELV   HGT
        -- -------- -------- -------- -------- ----- -----
        nn xxxxxxxx yyyyyyyy xxxxxxxx yyyyyyyy eeeee hhhhh
        01   8857.0   -400.0   8857.0   -412.0   4.4   8.0
        02   8572.0   -445.0   8572.0   -463.0   4.4   6.0
SECTION 12
           = FLIGHT PATH
           FAF       : 6.242  NAUTICAL MILES
           DATUM     : 7370.04    0.0    6.28
           TYPE      : MEASURED   (distance,measured,segmented,straight,
         *                           radial,orbit)
           VELOCITY :     200.0
           INCREMENT:      40.0
           DATA RATE:       0.2
         *  IF "straight" SUFFICIENT DATA IS AVAILABLE TO COMPUTE FLIGHT PATH
         *  IF "radial" ENTER ANGLE,ELEVATION & STARTING AND ENDING DISTANCES
         *              (nm from dme/p)
           ANGLE: aaaaaaaa
           SDIST: dddddddd
           EDIST: dddddddd
           ELEV : eeeeeeee
         *  IF "orbit" ENTER RADIUS (nm from dme/p) & ELEVATION
           RADIUS: rrrrrrrr
           ELEV  : eeeeeeee  (m.s.l.)
         *  IF "measured" X,Y,Z COORDINATES AND TIME WILL BE READ FROM UNIT 15
         *      WITH VELOCITY AND DATA INCREMENT COMPUTED FROM INPUT
         *  IF "segmented" or "distance" ENTER SEGMENT #,X,Y,Z,VELOCITY AND
         *      INCREMENT
        ##    XS        YS        ZS       VEL       INC
        -- -------- -------- -------- -------- --------
        nn xxxxxxxx yyyyyyyy zzzzzzzz vvvvvvvv iiiiiiii
SECTION 13
           = PLOT SCALE LIMITS
         * FLIGHT PATH PLOTS:
                                X/Y PLOT     X/Z PLOT     D/Z PLOT
                               ----------   ----------   ----------
             MINIMUM X VALUE :  -2000.0 ft   -2000.0 ft       0.0 ft
             UNITS PER INCH  :   6000.0 ft    6000.0 ft    6000.0 ft
             MINIMUM Y VALUE :  -3000.0 ft    -500.0 ft    -500.0 ft
             UNITS PER INCH  :   1000.0 ft     500.0 ft     500.0 ft
         * AIRPORT LAYOUT PLOT:
                                X/Y PLOT
                               ----------
             MINIMUM X VALUE :  -2000.0 ft
             UNITS PER INCH  :   2000.0 ft
             MINIMUM Y VALUE :  -6000.0 ft
             UNITS PER INCH  :   2000.0 ft
         * MULTIPATH DIAGNOSTIC PLOTS:
                                  M/D        SEP ANG     TIM DELAY    SHADOWING
                               ---------   ---------    ---------    ---------
             MINIMUM X VALUE :    1.0 nm      1.0 nm       1.0 nm       1.0 nm
             UNITS PER INCH  :    1.0 nm      1.0 nm       1.0 nm       1.0 nm
             MINIMUM Y VALUE :  -25.0 db    -15.0 deg      0.0 ns     -25.0 db
             UNITS PER INCH  :    5.0 db      5.0 deg    200.0 ns       5.0 db
         * RECEIVER OUTPUT ERROR & FILTERED ERROR PLOTS:
                                  RAW          PFE          CMN
                               ---------    ---------    ---------
             MINIMUM X VALUE :    1.0 nm       1.0 nm       1.0 nm
             UNITS PER INCH  :    1.0 nm       1.0 nm       1.0 nm
             MINIMUM Y VALUE :  -0.30 deg    -0.30 deg    -0.30 deg
             UNITS PER INCH  :   0.10 deg     0.10 deg     0.10 deg
END DATA
```